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Effect of Various Control Strategies on Gasoline Compression Ignition Engine: A Review

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ABSTRACT

This paper introduces a new alternative combustion concept as well as a detailed overview of the technique. GCI (gasoline compression ignition) is a promising advanced combustion mode for increasing fuel economy and lowering emissions. This is an innovative engine technology that uses the higher volatility of gasoline and auto-ignition temperature, as well as a diesel engine's higher compression ratio (CR), to reduce soot and NO_x *emissions while maintaining diesel engine efficiency. However, GCI engine has some challenges included cold starting, high CO and HC emissions, combustion stability at part load, and high combustion noise at medium-to-full load operations. Therefore, this paper reviews the experimental, numerical, and optical studies to go over various aspects of GCI engine technology, such as its combustion characteristics and controls. Furthermore, this paper examines some experimental studies to assess the potential benefits of GCI technology before pointing out future works. In various control strategies on GCI engines, the fuel injection strategy is the best solution to control the distribution of mixture concentration in the cylinder; adding additives into gasoline can change the reactivity of fuel and extend the lower limit of the stable combustion load of the GCI combustion method and coupling control strategies may be used to achieve stable combustion.*

1. INTRODUCTION

There are currently no viable alternatives capable of completely replacing reciprocating internal combustion engines (ICEs). Electric and hybrid electric vehicles are potential substitutes for ICEs. Electric and hybrid electric vehicles, on the other hand, will be better suited for short-distance trips and will fit better in the light-duty vehicle category. As a result, combustion engines are expected to be around for several decades, if not centuries, as long as more fuel-efficient and cleaner alternatives are made available. As a result, in the current scenario, research focusing on improving fuel conversion efficiency and reducing harmful emissions from ICEs is both justified and required [1].

Modern diesel engines are more efficient and emit lower tail-pipe CO and HC emissions than spark ignition (SI) engines, but they emit more PM (particulate matter) and NO_x, both of which are harmful to human health and the environment. To control NO_x and PM emissions at the same time, a diesel engine requires an advanced exhaust gas after-treatment system, such as a diesel particulate filter (DPF) and selective catalytic reduction (SCR) system, which increases system complexity and total vehicle cost. PM and NO_x emissions from CI engines can be reduced by increasing fuel-air mixing (turbulence) before combustion begins [1], [2].

The auto-ignition and oxidation reactions in conventional compression ignition (CI) engines are highly dependent on spray disintegration and mixing actions. Soot or PM is formed when localized rich regions form in the combustion chamber during the mixing-controlled combustion period. A stoichiometric region exists as well, which results in higher NO_x emissions due to the presence of higher temperature. Various engine operating strategies, such as exhaust gas recirculation (EGR), charge boosting devices, and ultra-high pressure fuel injection systems, have been developed in a variety of ways to reduce engine exhaust emissions and improve engine efficiency [1], [2]. Furthermore, to meet emission regulations, after-treatment techniques such as diesel particulate filter, selective catalytic reduction (SCR), and diesel oxidation catalyst are commonly used. The after-treatment techniques do not reduce all exhaust emissions to the desired level without causing any adverse effects, and such system components increase back-pressure, resulting in a decrease in thermal efficiency. Although after-treatment techniques are effective at reducing soot and NO_x emissions, they consume more fuel. Improving the combustion process is a common way to produce more output power while emitting less exhaust. Homogeneous air-fuel mixtures can eliminate soot

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formations, and lower equivalence ratios (φ) can reduce NO_x emissions. Researchers are focusing on low temperature combustion (LTC) to achieve the required emission levels and engine efficiency [1].

Based on the degree of premixing of the fuel-air mixture, LTC strategies are classified into two categories: homogeneous charge compression ignition (HCCI) and partially stratified charge compression ignition (PSCCI). The concept of HCCI is that the fuel/air mixture in the cylinder is less than stoichiometric before ignition. The fuel and air are mixed before the start of combustion in the HCCI combustion concept, and this mixture is auto-ignited due to the increase in temperature during the compression stroke. In fact, in generalized HCCI combustion concepts, one method/strategy is not limited to achieving a specific mode of combustion. In some cases, a single method/strategy can achieve more than one generalized HCCI combustion concept [3]. The PSCCI strategy may result in two types of stratification: thermal stratification and fuel concentration stratification in the cylinder. Thermal stratification is a technique used in the thermally stratified compression ignition (TSCI), partially premixed combustion (PPC), and spark-assisted compression ignition (SACI) strategies [4]. Fuel concentration stratification is possible with both single and dual fuels. In the fuel stratification category, the two main combustion phasing concepts are gasoline partially premixed combustion (PPC) and dual-fuel reactivity-controlled compression ignition (RCCI), which are widely researched due to their potential for better combustion phasing control, lower emissions, and higher thermal efficiency [5].

All LTC techniques provide flameless, homogeneous combustion of a premixed fuel-air mixture, resulting in very low NO_x formation due to lower adiabatic temperature and negligible soot formation due to the lack of a fuel-rich zone in the combustion chamber. However, because LTC produces higher CO and HC tail-pipe emissions due to a decrease in exhaust gas temperature, exhaust gas after-treatment devices are required to control CO and HC emissions [1].

The author's primary motivation for writing this review paper is to discuss various aspects of GCI engine technology, including combustion characteristics and controls. Furthermore, this paper examines preliminary experimental studies to assess the potential benefits of GCI technology. As a result, to assist other researchers in taking the next step in the field, as well as to assist them in determining what steps may need to be taken.

2. GASOLINE COMPRESSION IGNITION ENGINE TECHNOLOGY

Gasoline compression ignition (GCI) is a sophisticated engine technology that replaces diesel in CI engines with low-octane gasoline. In comparison to diesel operation, gasoline is more volatile and has a high resistance to auto-ignition, allowing for more homogeneous mixing of fuel-air before SoC. GCI technology combines the advantages of CI engines' higher compression ratio operation with the advantages of gasoline. This new engine-fuel system is expected to be cost-effective due to the use of low-octane gasoline, which is less expensive and can help reduce exhaust emissions such as NO_x and PM simultaneously.

Gasoline compression ignition (GCI) is an advanced LTC technique that can address diesel engine issues. At low load, the GCI engine operates in fully pre-mixed homogeneous combustion mode (similar to HCCI), in partially pre-mixed combustion (PPC) mode at medium load, and in diffusion-controlled combustion (similar to a diesel engine) mode at high load. Partially pre-mixed combustion (PPC) falls between the HCCI and CI combustion modes in terms of mixture homogeneity. PPC mode burns a fuel-air mixture using a combination of diffusion and pre-mixed mechanisms with bulk auto-ignition. At low loads, fuel is injected during the intake stroke or at the start of the compression stroke to achieve greater mixture homogeneity, whereas at high loads, gasoline is injected directly into the combustion chamber near the top dead center (TDC) like diesel. Because the ignition delay decreases with increasing engine load in a GCI engine, the level of fuel stratification must be improved. As a result, auto-ignition accounts for a small portion of fuel combustion, with the diffusion process accounting for the vast majority of fuel combustion.

The level of fuel stratification in a GCI engine has a significant impact on auto-ignitability, combustion phasing, combustion stability, and emissions depending on engine operating conditions. The fuel injection strategy can be used to control fuel stratification. As a result, GCI is a more practical technique than HCCI and can be used in commercial diesel engines for a wider operating range with improved combustion stability. According to the level of fuel stratification, GCI combustion modes are divided into three categories: partial fuel stratification (PFS), medium fuel stratification (MFS), and high fuel stratification (HFS). PFS is used to prepare a homogeneous charge at part-load conditions, with the first injection occurring either into the port or directly in the intake stroke. The main injection occurs during the compression stroke to achieve the desired level of fuel stratification and to auto-ignite the charge, allowing the engine to achieve low emissions while producing an acceptable level of combustion noise. With a slight increase in the fuel stratification level in MFS, the level of premixed charge decreases slightly. In MFS mode, all injections occur during the compression stroke, with the final injection occurring near TDC to trigger the premixed charge. At a high load, the GCI engine uses a high level of fuel stratification with no or very little premixed charge. In HFS mode, all injection events in HFS mode occur near TDC during the compression stroke. Under this condition, the combustion is not flameless. In GCI combustion, fuel injection pressure (FIP) varies to achieve the desired level of fuel stratification.

One of the most promising combustion concepts for achieving low pollutant emissions and high efficiency is gasoline compression ignition (GCI). The knock phenomenon, on the other hand, is an impediment to GCI combustion. Wei *et al.* investigated this experimentally (2018) [6]. The tests were conducted using commercial gasoline with a RON of 92, a constant engine speed of 1500 rpm, and a constant fuel supply mass of 18 mg/cycle. They demonstrated that the combustion processes of the two combustion modes differ significantly. Knock in SI engines is a random phenomenon caused by end gas auto-ignition. Knock in GCI engine, on the other hand, is attributed to local rapid burning rate, which did not occur at random.

By using low octane fuel, the GCI engine technology can reduce vehicle operating costs while maintaining high engine efficiency. However, the technology faces significant challenges, such as low-load combustion stability, high CO and HC emissions, combustion noise and rate of pressure rise (RoPR) at medium and high loads, and so on. The majority of issues can be solved by optimizing the combustion process.

3. EFFECT OF VARIOUS CONTROL STRATEGIES ON GCI ENGINE

Cold starting issues, high HC and CO emissions, combustion instability at low loads, and high RoPR at medium and high loads are the main issues associated with the GCI technique. GCI combustion, like other engine combustion processes, is heavily reliant on fuel properties, optimal injection strategies, and engine operating characteristics. By optimizing injection strategies, GCI technology can be effectively implemented [7]-[10]. The following sub-sections describe various control strategies that can be used in GCI combustion to achieve satisfactory engine performance.

3.1 Injection Strategy

Fuel injection strategies have a significant impact on engine combustion, performance, and tailpipe emissions [10]. Split injection strategies in GCI engines can achieve the desired level of combustion noise and knock resistance. The first injection pulse in multi-injection technology controls the level of premixed charge (mixture homogeneity), and the second injection pulse controls the combustion phasing (ignition timing). Zou *et al.* (2018) [11] investigated the effects of fuel injection strategy on the efficiency and emissions of a heavy-duty engine with gasoline compression ignition when operating at high load. They investigated the effects of delaying the intake valve closing timing (IVCT), a two-pulse fuel injection strategy, and injection pressure coupled with IVCT on combustion and emissions under high-load conditions using a single-cylinder engine modified from a heavy-duty compression ignition engine and operating in the GCI mode. They demonstrated that: (1) when the IVCT was delayed, the engine compression ratio decreased, reducing the temperature and pressure inside the cylinder and increasing the fuel delay timing. This helps to reduce soot emissions while also increasing the engine's high load limit. Using IVCT under high-load conditions can reduce heat transfer, exhaust, and incomplete combustion loss rates, increasing gross indicated thermal efficiency (ITE) by nearly 2.4 percent when compared to no IVCT delay, as shown in Figure 1. (2) As shown in Figure 2, combining IVCT delay, two-pulse injection, and appropriate injection pressure can reduce the fuel mixing time, resulting in lower ringing intensity (RI) and clean combustion at high engine load. (3) When operating at high loads and with the same pilot injection ratio, lowering the injection pressure helps to reduce unburned emission because the maximum in-cylinder average combustion temperature is highest. However, as illustrated in Figure 3, the level of NO_x emissions is also the highest.

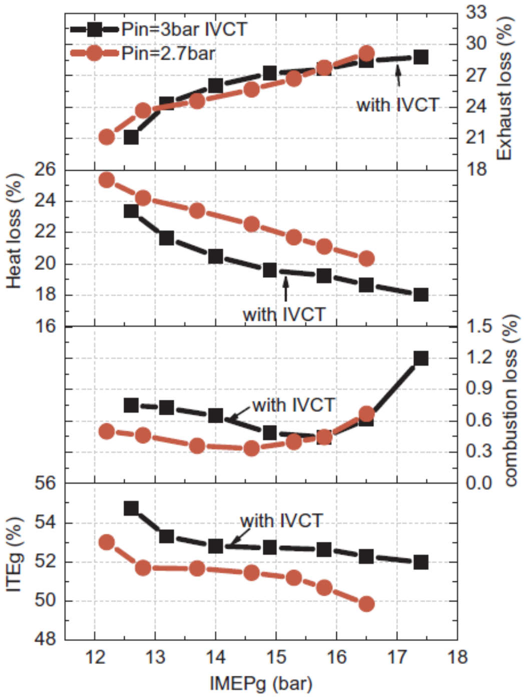


Fig. 1. Efficiencies as functions of IMEP with/without IVCT delay [11].

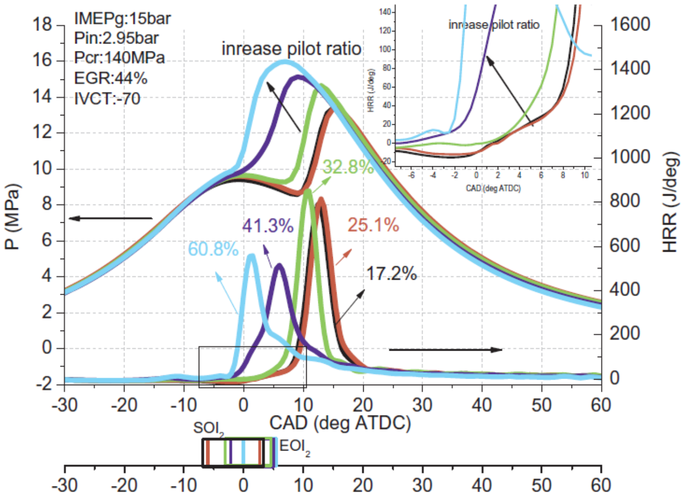


Fig. 2. Cylinder pressure and HRR for different pilot injection ratios [11].

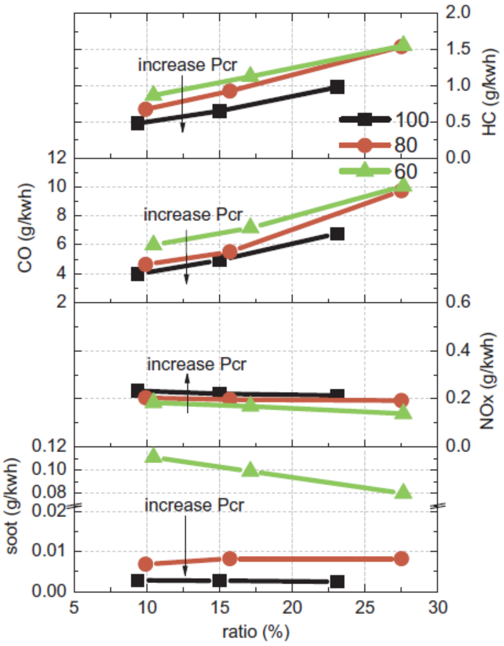
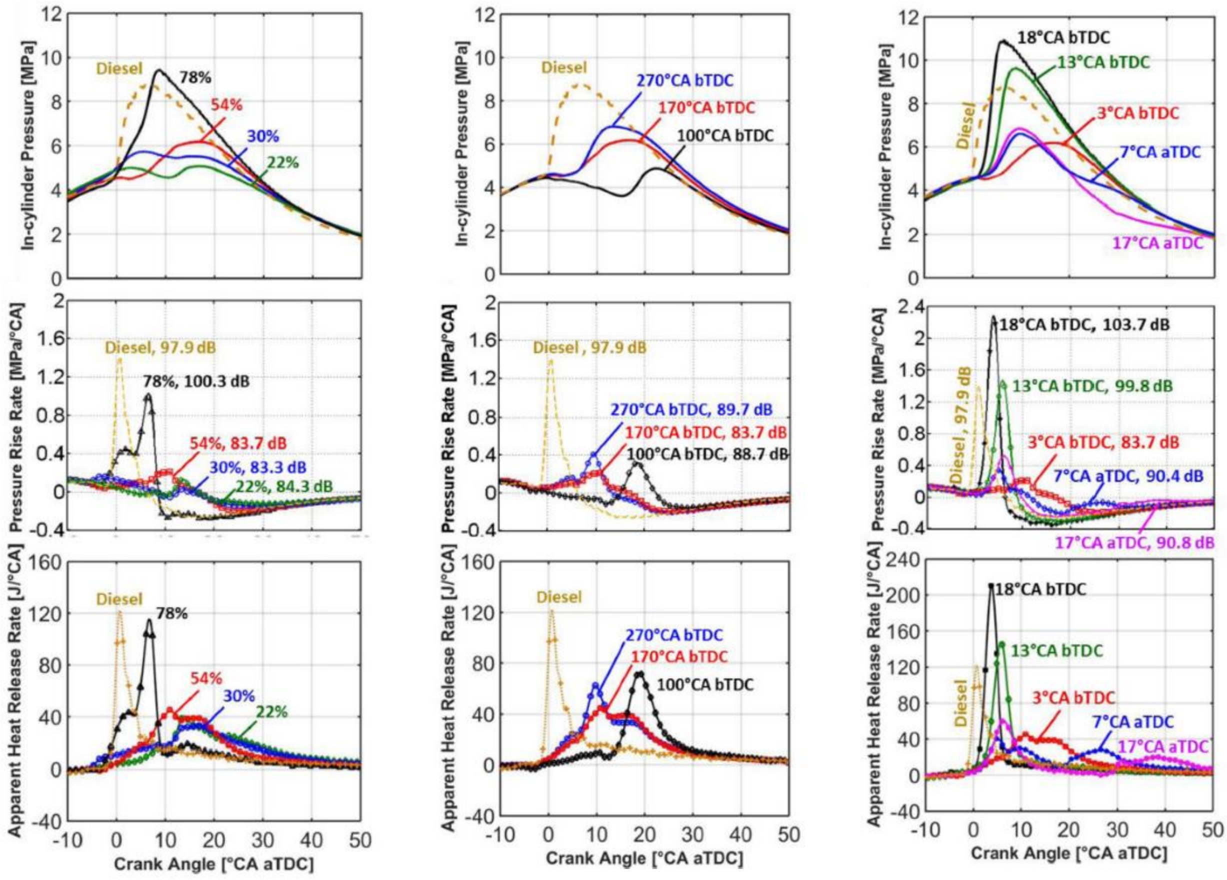


Fig. 3. Emissions as functions of pilot ratio and injection pressure [11].

Thongchai and Lim [12] investigated the effect of injection strategy on the combustion characteristics and exhaust emissions of a gasoline-fueled compression ignition engine. Their findings revealed that complete combustion was achieved at high injection pressure. Increased injection pressure improved combustion stability. Furthermore, exhaust emissions (NO_x and HC) were reduced.

Woo *et al.* [13] tested the engine performance and emissions of an ethanol-fueled gasoline compression ignition (ECI) engine in a single-cylinder light-duty common-rail diesel engine. The authors investigated how to optimize the double injection strategy based on three key parameters: the proportion of first and second injection mass, first injection timing, and second injection timing. According to the results of the experiments, a higher proportion of the first injection results in a higher in-cylinder pressure, pressure rise rate, and apparent heat release rate. These result in advanced combustion phasing, which increases net indicated engine efficiency while decreasing indicated specific fuel consumption (ISFC). Reduced smoke emissions result from a decreased first injection proportion and, as a result, an increased premixing level. The combustion temperature rises, resulting in lower HC and CO emissions from the engine; however, NO_x emissions rise, along with noise. In terms of first injection timing variations, more advanced first injection tends to perform better, owing to the longer pre-combustion mixing time and thus increased mixture homogeneity. The advanced first injection, on the other hand, increases NO_x emissions because the increased mixture homogeneity causes more advanced combustion phasing, which raises the combustion temperature. Variations in second injection timing cause a regime shift in ECI combustion, with decreased IMEP and increased ISFC limiting late second injection while high noise and NO_x emission limiting early second injection. Figure 4 depicts the results.



(a) (b) (c)

Fig. 4. Effect of 1st injection proportion (a), 1st injection timing (b), and 2nd injection timing (c) on the in-cylinder pressure, PRR, and aHRR traces of ECI engine combustion [13].

Putrasari and Lim [14] investigated the GCI engine powered by gasoline-biodiesel blends. Their findings revealed that earlier injection of gasoline-biodiesel blends resulted in higher thermal efficiency, whereas delayed injection of gasoline-biodiesel blends resulted in lower HC and NO_x emissions. However, this study only looked at different injection starts with a single injection strategy.

The effects of the pilot-injection timing and the pilot-injection quantity on a double-injection GCI engine with a fixed main-injection timing were investigated by Kim and Bae [15]. Based on the experimental findings, they concluded that: (1) The double-injection GCI was an effective tool for reducing combustion noise and NO_x emissions when compared to the single-injection GCI, but it causes some loss of the fuel economy due to the increased heat loss by multiple injections during the longer combustion durations. (2) The multiple-injection strategy should be used to reduce combustion noise for stable operation of GCI even under low load conditions. However, finding the optimal condition of stable GCI combustion based solely on pilot injection quantity and timing is difficult. (3) As demonstrated by the researchers in [15], the double-injection GCI significantly reduced in-cylinder peak pressure and peak heat release rate. As the pilot injection timings were advanced, the maximum pressure rise rate was reduced by approximately 80%. As the timing of the pilot injection was advanced, the premixed combustion of the pilot injection became weaker, resulting in lower temperature and pressure before the main injection. Both the peak values of the in-cylinder pressure and the heat release rate were reduced during the advanced pilot injection, and the combustion of the main injection was maintained during the shorter period. (4) In terms of emissions, as the pilot injection timing advanced, HC and CO emissions decreased. An early pilot injection could result in an over-lean mixture region, which is the primary source of high HC and CO emissions. Furthermore, as the pilot injection timing was advanced, the lower temperature and pressure conditions near the TDC at which the main injection is initiated may cause locally fuel-rich regions, which is the primary cause of the dramatic increase in CO emission. Because of the lower combustion temperature, the reduction in NO_x emissions with the double-injection strategy can now be easily estimated. Except for the soot emission, the emission levels of the pilot injection GCI became comparable with the emissions of the single injection GCI as the pilot injection quantity increased, owing primarily to the decrease in the main injection quantity. Because of the complete combustion of the pilot injection, the HC emission was reduced. Because of the formation of locally fuel-rich regions by the main injection, CO emissions and soot formation were slightly increased. Furthermore, as the combustion temperature rises, the amount of NO_x emitted rises as the pilot injection quantity rises.

Gasoline compression ignition mode is one of the low-temperature combustion strategies that use gasoline instead of diesel fuel, and it has better ignition controllability than the other low-temperature combustion modes. The main issue in commercializing this engine is the difficulty in starting at low loads and the maximum pressure rise rate at high loads. To address this issue, Zhong *et al.* [16] investigated the efficacy of gasoline/hydrogenated catalytic biodiesel blends at various loads using single and double injection strategies. They concluded from their experiments that: (1) Running a gasoline compression ignition engine at all loads with gasoline/hydrogenated catalytic biodiesel blends without increasing the intake temperature or using other assist methods is successful. (2) As the proportion of hydrogenated catalytic biodiesel in gasoline increases, the peak cylinder pressure, heat release rate, and ignition delay decrease while combustion duration increases. (3) Increasing the proportion of hydrogenated catalytic biodiesel in gasoline reduces NO_x emissions while increasing PM emissions has the opposite effect. CO and HC emissions are higher at all loads, particularly at low loads. (4) When double injection strategies are used, the in-cylinder pressure and heat release rate decrease as the pilot injection ratio increases at low load, but the opposite trend occurs at high load. Furthermore, Zhang *et al.* (2019) [17] investigated the effect of a blended ratio of hydrogenated catalytic biodiesel (HCB) into gasoline on the combustion and emission characteristics of a heavy-duty diesel engine. Their findings revealed that as the HCB proportion increases, ignition performance improves significantly, maximum combustion pressure can be effectively suppressed, and combustion stability under low load conditions improves significantly. The gas emissions of NO_x, CO, and HC can be significantly reduced by increasing the HCB ratio, but the PM emission increased slightly.

The reasonable fuel injection strategy has always been the focus for improving the combustion stability of GCI combustion mode at low loads. Furthermore, by carefully designing the number of injections, the timing of pilot injection, and the ratio of pilot injection quantity, the concentration distribution of the mixture, the ignition timing, and the combustion phasing are effectively controlled. As a result, the mixture can be completely burned, allowing the GCI combustion method to achieve lower NOX and soot emissions in a wider range of working conditions while increasing thermal efficiency. One of the most effective injection techniques for controlling charge thermal stratification and concentration was the control of injection pressure. The primary reason for progressive injection pressure increases in GCI engines is increased spray kinetic energy, which can promote droplet fragmentation, evaporation, and air-fuel mixing while also ensuring a better combustion process and lower emissions [18]-[24].

3.2 Fuel Ignition Quality

Because gasoline has a lower cetane number, it has a longer ignition delay before SoC. It should be injected earlier in the compression stroke at lower in-cylinder pressure and temperature conditions that are not conducive to gasoline auto-ignition.

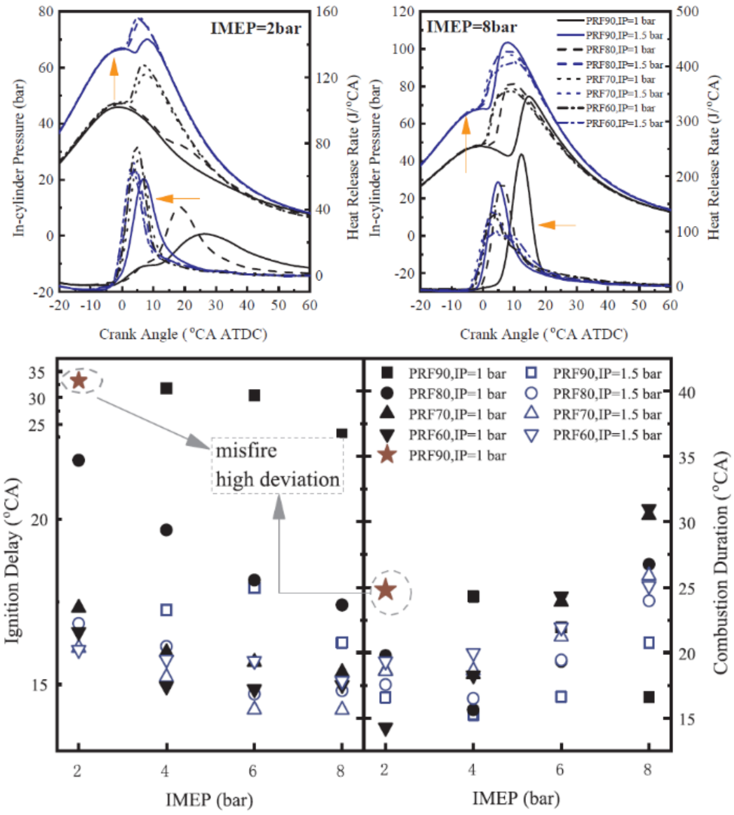


Fig. 5. Effects on intake air pressure (IP) on in-cylinder pressure, heat release rate, ignition delay, and combustion duration [25].

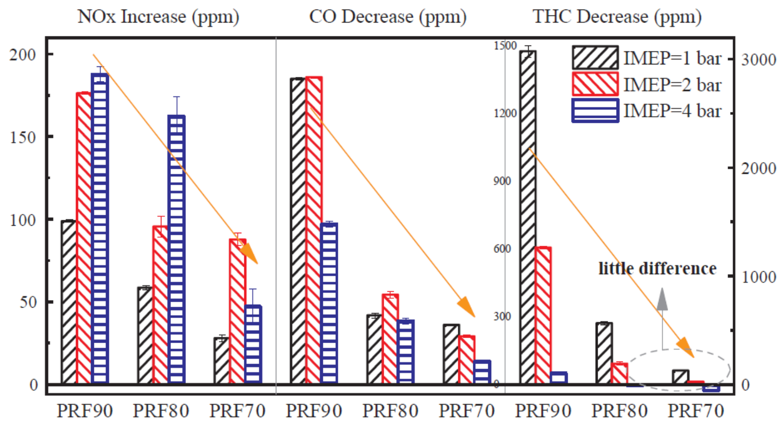


Fig. 6. Effect of intake temperature on NO_x, CO, and THC [25].

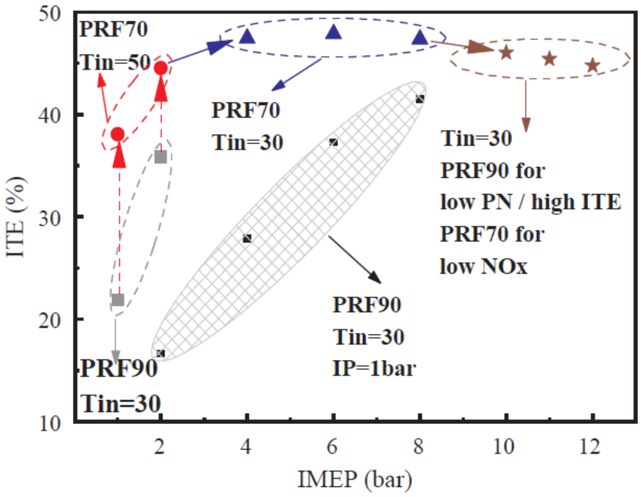


Fig. 7. The enhanced ITE under all loads [25].

Jiang *et al.* (2019) [25] investigated the performance and emissions characteristics of a GCI engine using four different primary reference fuels (PRFs) with research octane numbers of 60, 70, 80, and 90, dubbed PRF60, PRF70, PRF80, and PRF90. The effects of intake air pressure (IP) on in-cylinder pressure, heat release rate, ignition delay, and combustion duration are depicted in Figure 5. Because of the longer ignition delay period, combustion was unstable with PRF90 at 2 bar IMEP. As shown in Figure 6, increasing the intake temperature reduces CO and THC emissions under low loads but increases NO_x emissions due to the higher in-cylinder temperature. The authors proposed that using PRF70 with intake air heating at part load, the GCI engine delivered better performance and engine efficiency (IMEP between 1 and 4 bar). PRF70 performed well at medium loads (IMEP between 4 and 8 bar) and PRF90 performed well above IMEP of 8 bar without intake air heating. As shown in Figure 7, the indicated thermal efficiency (ITE) with PRF70 could reach up to 47 percent under medium load.

Goyal *et al.* (2019) [26] investigated the effect of fuel ignition quality and first injection proportion on charge premixing level and mixture homogeneity in a single-cylinder small-bore diesel engine with double-injection-based gasoline compression ignition (GCI) combustion. According to the researchers, higher RON fuels and fixed pilot injection quantity result in greater premixing of fuel injected during the main injection event, which increases combustion noise and peak aHRR. Furthermore, they stated that increasing the RON of the test fuel improved engine efficiency but decreased it when increasing the first injection quantity. Higher RON with fixed mixture homogeneity, on the other hand, resulted in over-premixing of the second injection. Because of the high reaction temperatures, it increased engine-out NOx emissions, but it decreased engine-out HC, CO, and smoke, as shown in detail in Figure 8.

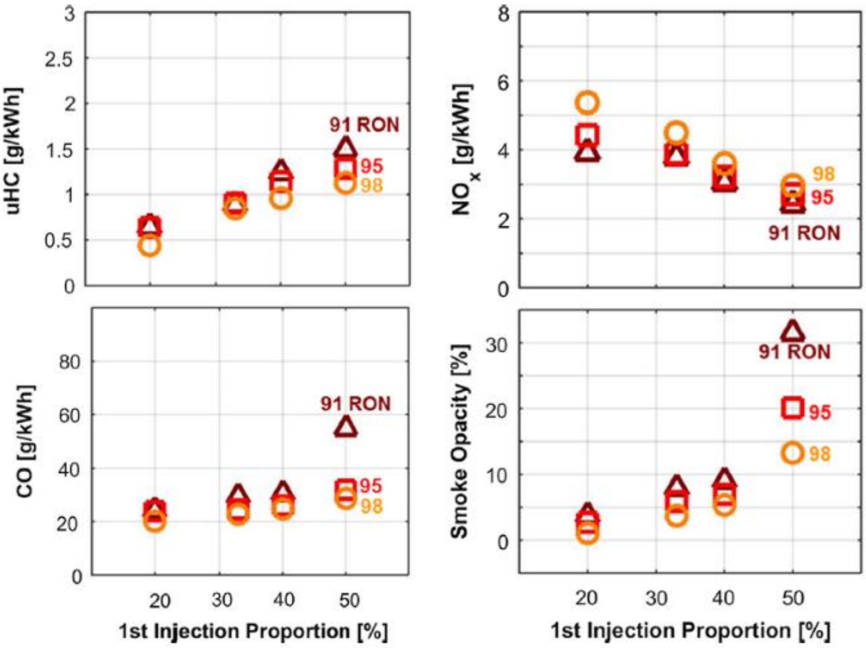


Fig. 8. Engine-out NO_x, HC, CO, and smoke emissions at different pilot injection proportions and fuel ignition quality at fixed combustion phasing (CA50 at 10^0 CA aTDC) [26].

Wang *et al.* (2020) [27] conducted a numerical study on low octane gasoline-like fuel compression ignition combustion at high load. The researchers investigated the performance and emissions of a GCI engine running on ten different primary reference fuels (PRFs). PRF0, PRF20, PRF40, PRF60, PRF70, PRF80, PRF85, PRF90, PRF92, and PRF100, in that order. The volume ratio of iso-octane in the mixture of n-heptane and iso-octane, representing the octane number, is defined as the PRF number. As shown in Figure 9, as the fuel octane number is reduced, the ignition delay and maximum HRR (heat release rate) increase noticeably. Concerning emissions, they discovered that the PRF70 had the best performance and emissions of any tested fuel, implying that the PRF70 has the potential to improve the combustion process of GCI at high load, as shown in Figure 10.

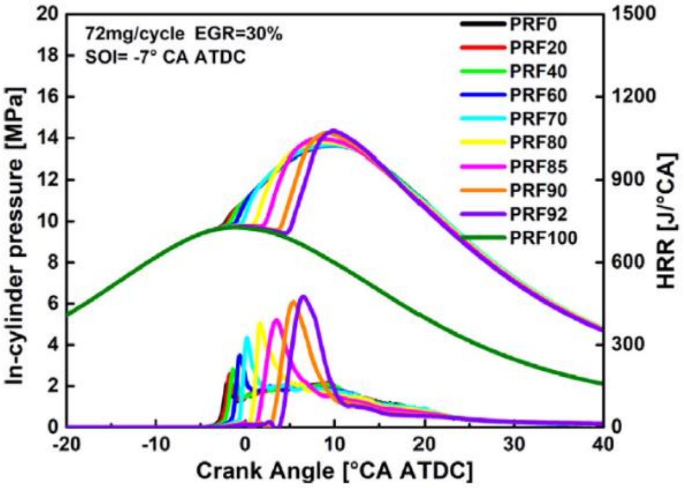


Fig. 9. Effect of fuel octane number on in-cylinder pressure and HRR [27].

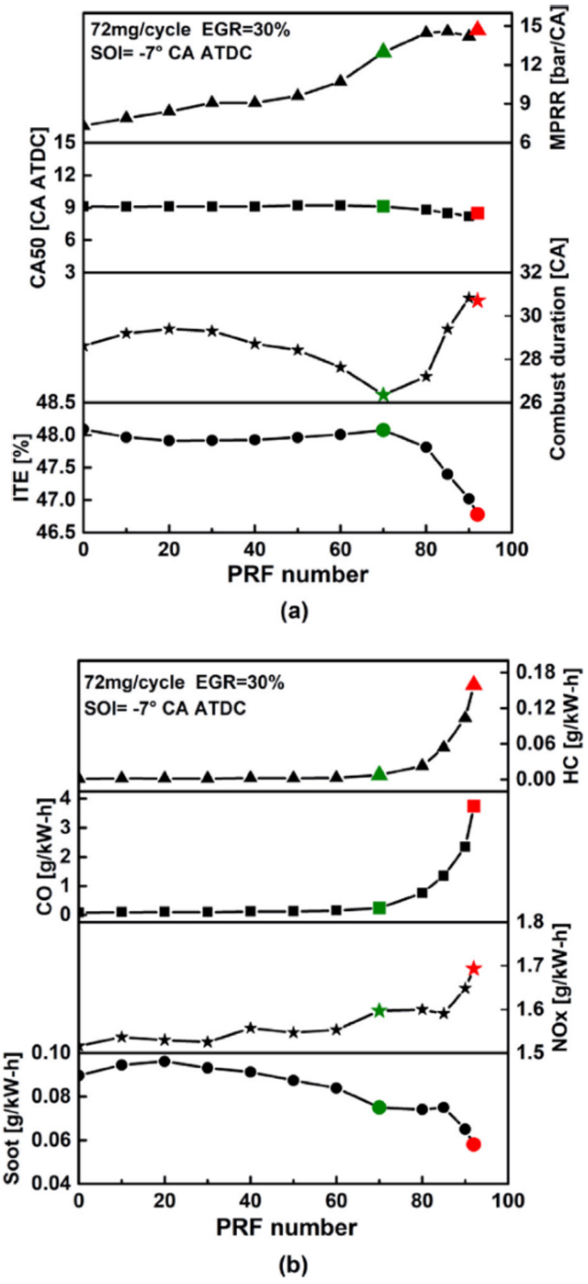


Fig. 10. Effect of PRF number on combustion (a) and emission of GCI engine [27].

3.3 *EGR Strategy*

By controlling the in-cylinder temperature and oxygen level, effective control of used EGR (Exhaust Gas Recirculation) reduces NO_x emissions. Zhou *et al.* [28] investigated the effect of iEGR (Internal Exhaust Gas Recirculation) on the combustion characteristics of a gasoline compression ignition engine operating at low to idle speeds. Because of the competitive relationship, they discovered that the burning rate increases first and then decreases as the iEGR ratio increases from low to high. Under idle conditions, the heating effect dominates the combustion process, improving combustion stability. By using a high iEGR ratio, the low load limit was successfully extended. Meanwhile, the idling fuel consumption per unit displacement approaches that of commercial vehicles.

Internal exhaust gas recirculation (iEGR) technology is used to broaden the operating range and provide a GCI engine with combustion stability. Pan *et al*. (2020) [29] investigated the effects of iEGR rate (10 - 90%) and excess air ratio (λ = 1.0 - 4.0) on GCI engine combustion performance and emissions. They discovered that (1) the heat effect caused by iEGR has a significant effect on ignition stability at low loads, which in turn significantly improves the ignition environment. For stable ignitibility, a stable maximum in-cylinder pressure and HRR would be obtained at λ = 1.5 and 30 percent or 60 percent iEGR. (2) To obtain the optimal ignition delay time and combustion phase, iEGR ranges of 30% - 60% could be considered with λ = 1. (3) High torque can be obtained when the iEGR is between 20% and 60% and λ = 1 or 1.5. (4) When appropriate iEGR rates and are used in GCI engines, CO, uHC, and NOx emissions would have a less negative impact on the environment.

Jiang *et al.* (2019) [30] investigated the effects of exhaust gas recirculation and fuel octane number in the combination. Researchers demonstrated that by adjusting the fuel octane number and EGR rate, high efficiency and low NOx emissions could be obtained under all loads. PRF70 can achieve an indicated thermal efficiency of more than 47 percent by using EGR rates of 30 percent and 40 percent at 6 bar and 8 bar, respectively. Under low and medium loads, increasing the EGR rate reduces the PM emissions of all research fuels because it delays the combustion phase, which is conducive to fuel atomization and raises the in-cylinder temperature, lowering the PM emission. Under high loads, however, increasing the EGR rate increases PM emission due to decreased volumetric efficiency.

In-EGR is gaining popularity as one of the most promising strategies for controlling GCI combustion. In-EGR technology traps high-temperature exhaust gas, resulting in a reduction in incomplete combustion products. Aside from that, high-temperature residual gas can improve the initial thermodynamic state of the working fluid in the cylinder and reform the fuel to form a large number of small molecules with high reactivity, such as O, H, OH, and so on. When compared to the In-EGR strategy, the internal and external EGR coupling strategy can significantly improve the emission performance of the GCI combustion mode across the board [28], [31]-[35].

3.4 Other Control Techniques

Zhou *et al*. [22] investigated how to improve the low-load combustion stability and cold-firing capacity of a gasoline compression ignition engine. Their research combined negative valve overlap (NVO), in-cylinder fuel reforming, and intake preheating to achieve rapid firing under cold-start and subsequent warm-up conditions. The results showed that starting the injection during the intake stroke yielded the best fuel economy, while starting the injection during the compression stroke had the potential to extend the low load limit. Due to fast heat accumulation and the presence of highly reactive products as a result of in-cylinder fuel reforming, the NVO injection strategy was shown to be the most suitable injection strategy for firing a GCI engine. However, failure of engine firing was observed with cold intake air and coolant due to the absence of chemical reactions and heat accumulation. Under these conditions, intake preheating improves firing capacity and allows the engine to start successfully within five cycles. When the coolant is cold, intake preheating is required, and the fuel supply must be sufficient to avoid firing failure; however, when the coolant is hot, intake preheating is not required, and the fuel supply must be carefully controlled to maximize the duration of the unstable firing process.

Xu *et al.* (2020) [4] investigated the fuel/air mixing and combustion in a heavy-duty gasoline direct-injection compression ignition engine with different piston geometrical profiles, compression ratio, and injection timing in different LTC engine regimes. They discovered that with the same combustion timing, a higher CR results in lower NO_x but higher HC and CO emissions. In the transition regime, piston geometry has a significant impact on the combustion and emission processes, whereas it has a minor impact in the HCCI and PPC regimes. They demonstrated that high engine efficiency and low NO_x, CO, and HC emissions can be achieved in both the earlier PPC regime and the later transition regime.

Pinazzi *et al.* (2018) [36] investigated the effect of injector spray angle ratio on low-load operation in a gasoline compression ignition (GCI) engine using a custom 1460 (UA146) umbrella angle diesel injector and a second injector with a 700 umbrella angle (UA70), as shown in Figure 11. The researchers demonstrated that using the narrower UA70 injector improved the local mixture strength. Despite the low levels of soot and NO_x emissions, gasoline combustion resulted in high levels of CO and HC emissions.

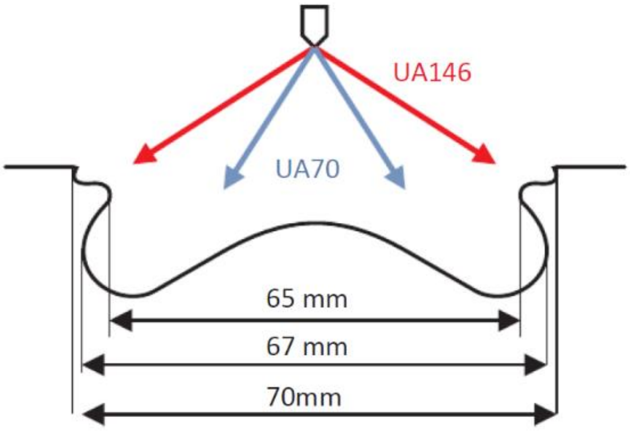


Fig. 11. Schematic diagram of two different injectors [36].

Controlling the initial thermodynamic state of the reactants allows for an increase in compression ratio, an extension of the low-load limit of GCI combustion, which includes specific technologies: Intake heating, intake boost, and spark-assisted ignition are all options. Increased intake temperature can meet the temperature requirement of spontaneous ignition, while intake boost can achieve a lower equivalence ratio, both of which can help to successfully start the combustion in a low-pressure and low-temperature environment. Spark assistance can also be used to improve spontaneous ignition if necessary [24], [37]-[47].

In fact, due to its high-octane number, gasoline fuel may not auto-ignite under the lean fuel-air mixture conditions typical of un-throttled CI operations at low load. Several works have been carried out to find a solution for overcoming the low load limitations of GCI engines, in which different fuels were used. According to [48], low octane gasoline with RONs ranging from 70 to 85 is the best fuel to use in GCI engines because they have enough autoignition propensity to achieve low load while retaining the benefits of conventional gasoline at higher loads. The authors of [49] investigated the challenges of achieving a stable low load condition using commercial gasoline in a light-duty CI engine. The effect of several parameters, including uncooled exhaust gas recirculation (EGR), injection timing, injection pressure, and nozzle geometry, was investigated, emphasizing the importance of concentrating a stratified enough fuel-air mixture into the piston. They demonstrated the ability of ozone to overcome GCI low load limitations and to extend the GCI operating range toward lower load without the use of boosting or variable valve train in [50], [51]. They demonstrated that in order to take advantage of the ozone effect, the injection strategy had to be modified: a first injection during the intake stroke was required to obtain the ozone-promoting effect, while a second injection during the compression stroke was used to induce the fuel stratification required for controlling the combustion phasing and avoiding excessive heat release rate. Chuahy *et al.* investigated the effects of distillation characteristics and aromatic content on performance and emissions in a multi-cylinder GCI engine in [52]. According to their findings, the aromatic content of the fuel had a significantly greater impact on gaseous HC and particulate matter emissions. According to the findings, a low aromatic fuel with high volatility is preferred to reduce gaseous HC, particulate matter, and soot emissions.

4. CONCLUSIONS

GCI (gasoline compression ignition) is a promising combustion mode for improving fuel economy and lowering emissions. Therefore, this paper reviews the experimental, numerical, and optical studies to go over various aspects of GCI engine technology. In various control strategies on GCI engines, the fuel injection strategy is the best solution to control the distribution of mixture concentration in the cylinder; adding additives into gasoline can change the reactivity of fuel and extend the lower limit of the stable combustion load of the GCI combustion method; and coupling control strategies may be used to achieve stable combustion. The following conclusions can be drawn by summarizing them:

1. GCI is a promising engine combustion technology that increases engine efficiency while lowering tail-pipe NO_x and PM emissions. GCI engines use three levels of fuel stratification: partial, moderate, and high, allowing for the optimization of vehicle performance and emissions under varying operating conditions.
2. Because of the benefits of GCI engine technology, the new concept can reduce vehicle operating costs by using low octane fuel while maintaining high engine efficiency. As a result, research and development efforts are required to address the issues associated with GCI engine technology before it can be used in commercial vehicles.
3. Cold starting and idle conditions; combustion stability at low load; combustion noise and RoPR at medium and high load; high CO and HC emissions; and hardware optimization are the main challenges of GCI engine technology (such as chamber design, piston, *etc.*). Most problems, however, can be solved by optimizing the combustion process, such as by optimizing injection strategies.
4. The practical limits of controlling PM and NO_x emissions from diesel engines have been reached. GCI will be an alternative technology for reducing emissions from CI engines while maintaining engine efficiency.
5. The GCI technology can benefit both the automotive industry and the oil industry by lowering well-to-wheel GHG emissions as well as refining costs.
6. In a GCI engine, a skewed fuel injection strategy can help reduce combustion noise to a desired level.
7. The use of NVO, early first injection, EGR, and glow-plug can improve the part load stability of a GCI engine.
8. Intake heating, intake boost, spark assistance, and internal EGR can all help to improve the initial thermodynamic state of reactants.
9. It's necessary to improve the thermodynamic state in the cylinder under low-load conditions by adding additives into gasoline or coupling control strategies.

This review demonstrates that in GCI combustion mode, it is possible to achieve high efficiency while emitting low NO_x and soot emissions. However, significant R&D efforts in the following directions are required to commercialize GCI vehicles in the current market:

- GCI engines must improve their combustion stability at low loads.
- Control of the combustion process during cold start and idle.
- To control high noise and high rate of pressure rise (RoPR) at medium and high engine loads, optimized injection strategies would be required.
- Developing an exhaust gas after-treatment system at low exhaust gas temperatures is critical for reducing HC and CO emissions.
- It is critical to reducing overall system complexity and costs while ensuring easy adaptability of the GCI technique to existing CI engines.
- The piston geometry and fuel injector must be optimized.
- Optimize injectors and injection systems to correspond to reasonable fuel injection strategies.

- Increase the compression ratio of the engine to improve the thermodynamic.

NOMENCLATURE

GCI	gasoline compression ignition
CR	compression ratio
NOx	nitrogen oxides
CO	carbon monoxide
HC	hydrocarbon
ICEs	internal combustion engines
SI	spark ignition
PM	particulate matter
DPF	diesel particulate filter
SCR	selective catalytic reduction
CI	compression ignition
EGR	exhaust gas recirculation
LTC	low temperature combustion
HCCI	homogeneous charge compression ignition
PSCCI	partially stratified charge compression ignition
TSCI	thermally stratified compression ignition
SACI	spark-assisted compression ignition
PPC	partially premixed combustion
RCCI	reactivity-controlled compression ignition
TDC	top dead center
PFS	partial fuel stratification
MFS	medium fuel stratification
HFS	high fuel stratification
FIP	fuel injection pressure
RON	research octane number
rpm	revolutions per minute
RoPR	rate of pressure rise
IVCT	intake valve closing timing
ITE	indicated thermal efficiency
IMEP	indicated mean effective pressure
HRR	heat release rate
ISFC	indicated specific fuel consumption
IMEP	indicated mean effective pressure
HCB	hydrogenated catalytic biodiesel
SoC	start of combustion
PRFs	primary reference fuels
THC	total hydrocarbon
aHRR	apparent heat release rate
EGR	exhaust gas recirculation
iEGR	internal exhaust gas recirculation
NVO	negative valve overlap

REFERENCES

[1] Maurya R.K., 2018. *Characteristics and Control of Low Temperature Combustion Engines: Employing Gasoline, Ethanol and Methanol*. Cham: Springer International Publishing.

[2] Heywood J.B., 2018. *Internal Combustion Engine Fundamentals*. Second Edition. New York: McGraw-Hill Education.

[3] Kumar P. and A. Rehman. 2016. Bio-diesel in homogeneous charge compression ignition (HCCI) combustion. *Renewable and Sustainable Energy Reviews* 56: 536-550.

[4] Xu L., Bai X., Li Y., Treacy M., Li C., Tunestal P., Tunér M., and Lu X., 2020 Effect of piston bowl geometry and compression ratio on in-cylinder combustion and engine performance in a gasoline direct-injection compression ignition engine under different injection conditions. *Applied Energy* 280: 115920.

[5] Singh A.P., Sharma N., Agarwal R., and Agarwal A.K., 2020. *Advanced Combustion Techniques and Engine Technologies for the Automotive Sector*. Singapore: Springer Nature Singapore Pte Ltd.

[6] Wei H., Hua J., Pan M., Feng D., Zhou L., and Pan J., 2018. Experimental investigation on knocking combustion characteristics of gasoline compression ignition engine. *Energy* 143: 624-633.

[7] Liu H., Mao B., Liu J., Zheng Z., and Yao M., 2018. Pilot injection strategy management of gasoline compression ignition (GCI) combustion in a multi-cylinder diesel engine. *Fuel* 221: 116-127.

[8] Park W., Ra Y., Kurtz E., Willems W., and Reitz R. D., 2015. Use of Multiple Injection Strategies to Reduce Emission and Noise in Low Temperature Diesel Combustion. *SAE 2015 World Congress & Exhibition*. Detroit, United States, 21-23 April. Warrendale : SAE International.

[9] Qiu L., Cheng X., Liu B., Dong S., and Bao Z., 2016. Partially premixed combustion based on different injection strategies in a light-duty diesel engine. *Energy* 96: 155-165.

[10] Tang Q., Liu H., Li M., and Yao M., 2016. Study on the Double Injection Strategy of Gasoline Partially Premixed Combustion under a Light-Duty Optical Engine. *SAE International Journal of Engines*, 2016. 9(4): 2185-2193.

[11] Zou X., Liu W., Lin Z., Wu B., and Su W., 2018. An experimental investigation of the effects of fuel injection strategy on the efficiency and emissions of a heavy-duty engine at high load with gasoline compression ignition. *Fuel* 220: 437-445.

[12] Thongchai S. and O. Lim. 2017. Influence of Injection Strategy on a Compression Ignition

Engine Fueled with Gasoline. *Energy Procedia* 105: 1757-1763.

[13] Woo C., Goyal H., Kook S., Hawkes E., and Chan Q.N., 2016. Double Injection Strategies for Ethanol-Fuelled Gasoline Compression Ignition (GCI) Combustion in a Single-Cylinder Light-Duty Diesel Engine. *SAE 2016 International Powertrains, Fuels & Lubricants Meeting*. Baltimore, United States, 24-26 October. Warrendale: SAE International.

[14] Putrasari Y. and O. Lim. 2017. A study on combustion and emission of GCI engines fueled with gasoline-biodiesel blends. *Fuel* 189: 141-154.

[15] Kim D. and C. Bae. 2017. Application of double-injection strategy on gasoline compression ignition engine under low load condition. *Fuel* 203: 792-801.

[16] Zhong W., Tamilselvan P., Li Z., Qian Y., Zhang Y., Wang Q., He Z., and Lu X., 2019. Combustion and emission characteristics of gasoline/hydrogenated catalytic biodiesel blends in gasoline compression ignition engines under different loads of double injection strategies. *Applied Energy* 251: 113296.

[17] Zhang Y., Li Z., Tamilselvan P., Jiang C., He Z., Zhong W., Qian Y., Wang Q., and Lu X., 2019. Experimental study of combustion and emission characteristics of gasoline compression ignition (GCI) engines fueled by gasoline-hydrogenated catalytic biodiesel blends. *Energy* 187: 115931.

[18] An Y., Raman V., Tang Q., Shi H., Sim J., Chang J., Magnotti G., and Johansson B., 2019. Combustion stability study of partially premixed combustion with low-octane fuel at low engine load conditions. *Applied Energy* 235: 56-67.

[19] Mao B., Wang Q., Liu J., Liu H., Zheng H., and Yao M., 2017. Effects of gasoline viscosity and injection pressure on the performance and emissions of a multi-cylinder partially premixed combustion engine. *The Ninth International Conference on Modeling and Diagnostics for Advanced Engine*. Okayama, Japan. 25-28 July. Tokyo: The Japan Society of Mechanical Engineers.

[20] Goyal H. and S. Kook. 2019. Ignition process of gasoline compression ignition (GCI) combustion in a small-bore optical engine. *Fuel* 256: 115844.

[21] Cung K. and S. Ciatti. 2017. A Study of Injection Strategy to Achieve High Load Points for Gasoline Compression Ignition (GCI) Operation. *ASME 2017 Internal Combustion Engine Division Fall Technical Conference*. Washington, USA, 15-18 October. New York: The American Society of Mechanical Engineers.

[22] Zhou L., Hua J., Wei H., and Han Y., 2019. An experimental investigation on low load combustion stability and cold-firing capacity of a gasoline compression ignition engine. *Engineering* 5(3): 558-567.

[23] Ciatti S. and S.W. Subramanian. 2011. An experimental investigation of low-octane gasoline in diesel engines. *Journal of Engineering for Gas Turbines and Power* 133(9): 092802.

[24] An Y., Q.T., Vallinayagam R., Shi H., Sim J., Chang J., Magnotti G., and Johansson B., 2019. Combustion stability study of partially premixed combustion by high-pressure multiple injections with low-octane fuel. *Applied Energy 248:* 626-639.

[25] Jiang C., Li Z., Liu G., Qian Y., and Lu X., 2019. Achieving high efficient gasoline compression ignition (GCI) combustion through the cooperative-control of fuel octane number and air intake conditions. *Fuel* 242: 23-34.

[26] Goyal H., Kook S., and Ikeda Y., 2019. The influence of fuel ignition quality and first injection proportion on gasoline compression ignition (GCI) combustion in a small-bore engine. *Fuel* 235: 1207-1215.

[27] Wang H., Zhu H., Ma T., and Yao M., 2020. Numerical investigation on low octane gasoline-like fuel compression ignition combustion at high load. *Fuel* 270: 117532.

[28] Agarwal D., Singh S.K., and Agarwal A.K., 2011. Effect of exhaust gas recirculation (EGR) on performance, emissions, deposits and durability of a constant speed compression ignition engine. *Applied Energy* 88(8): 2900-2907.

[29] Pan M., Qian W., Wei H., Feng D., and Pan J., 2020. Effects on performance and emissions of gasoline compression ignition engine over a wide range of internal exhaust gas recirculation rates under lean conditions. *Fuel* 265: 116881.

[30] Jiang C., Huang G., Liu G., Qian Y., and Lu X., 2019. Optimizing gasoline compression ignition engine performance and emissions: Combined effects of exhaust gas recirculation and fuel octane number. *Applied Thermal Engineering* 153: 669-677.

[31] Balaji J., Ganesh Prasad M.V., Rao L.N., and Bandaru B., 2014. Modelling and experimental study of internal EGR system for NOX control on an off-road diesel engine. *SAE 2014 International Powertrains, Fuels & Lubricants Meeting*. Birmingham, United Kingdom, 20-23 October. Warrendale: SAE International.

[32] Dittrich P., Peter F., Huber G., and Kuehn M., 2010. Thermodynamic potentials of a fully variable valve actuation system for passenger-car diesel engines. *SAE 2010 World Congress & Exhibition.* Detroit, United States, 13-15 April. Warrendale: SAE International.

[33] Zhang X., Zheng Z.H., Reitz R., and Yao M., 2016. Experimental investigations of gasoline partially premixed combustion with an exhaust rebreathing valve strategy at low loads. *Applied Thermal Engineering* 108: 832-841.

[34] Xiangyu Z., Zunqing Z., Shube H., Yanfang L., Yuxuan Z., and Mingfa Y., 2018. Effects of the intake pressure on gasoline low temperature compression ignition. *Chinese Internal Combustion Engine Engineering* 39(1): 1-7.

[35] Zheng Z., H.C., Liu H., Chen P., Ma N., and Yang B., 2018. Effects of split injection parameters and

EGR on combustion and emissions of GCI. *Journal of Combustion Science and Technology* 24(4): 307-314.

[36] Pinazzi P.M., Hwang J., Kim D., Foucher F., and Bae C., 2018. Influence of injector spray angle and gasoline-diesel blending ratio on the low load operation in a gasoline compression ignition (GCI) engine. *Fuel* 222: 496-505.

[37] Weall A. and N. Collings. 2007. Investigation into partially premixed combustion in a light-duty multi-cylinder diesel engine fuelled gasoline and diesel with a mixture of. *Powertrain & Fluid Systems Conference and Exhibition*. Rosemont, United States, 29 October - 1 November. Warrendale: SAE International.

[38] De Nicolao G., Scattolini R., and Siviero C., 1996. Modelling the volumetric efficiency of IC engines: parametric, non-parametric and neural techniques. *Control Engineering Practice* 4(10): 1405-1415.

[39] Xiao G., Y.Z., Lang J., and Jiang G., 2014. Experiment of the effects of intake temperature on GCI engine combustion and emission characteristics. *Transactions of CSICE*. 125-130.

[40] Persson H., 2008. *Spark Assisted Compression Ignition,* SACI. Doctoral Thesis. Lund University, Lund, Sweden.

[41] Xie H., Yang L., Qin J., Gao R., Zhu H., He B.Q., and Zhao H., 2005. The effect of spark ignition on the CAI combustion operation. *Powertrain & Fluid Systems Conference & Exhibition*. San Antonio, United States, 24-27 October. Warrendale: SAE International.

[42] Pastor J.V., Garcia-Oliver J.M., Garcia A., Mico C., and Durrett R.P., 2013. A spectroscopy study of gasoline partially premixed compression ignition spark assisted combustion. *Applied Energy* 104: 568-575.

[43] Benajes J., Garcia A., Domenech V., and Durrett R., 2013. An investigation of partially premixed compression ignition combustion using gasoline and spark assistance. *Applied Thermal Engineering* 52(2): 468-477.

[44] Yao M., Zheng Z., and Liu H., 2019. Progress and recent trends in homogeneous charge compression ignition (HCCI) engines. *Progress in Energy and Combustion Science* 35(5): 398-437.

[45] Loeper P., Ra Y., Adams C., Foster D.E., Ghandhi J., Andrie M., Krieger R., and Durrett R., 2013. Experimental investigation of light-medium load operating sensitivity in a gasoline compression ignition (GCI) light-duty diesel engine. *SAE 2013 World Congress & Exhibition*. Detroit, United States, 16-18 April Warrendale: SAE International.

[46] Xiangyu Z., Zunqing Z., Shube H., Yanfang L., Yuxuan Z., and Mingfa Y., 2018. Effects of the intake pressure on gasoline low temperature compression ignition CICEE. *Chinese Internal Combustion Engine Engineering* 39(1): 1-7.

[47] An Y., Raman V., Tang Q., Shi H., Sim J., Chang J., Magnotti G., and Johansson B., 2019. Combustion stability study of partially premixed combustion with low-octane fuel at low engine load conditions. *Applied Energy* 235: 56-67.

[48] Kalghatgi G.T., 2015. Developments in internal combustion engines and implications for combustion science and future transport fuels. *Proceedings of the Combustion Institute* 35(1): 101-115.

[49] Kolodziej C., Kodavasal J., Ciatti S., Som S., Shidore N., and Delhom J., 2015. Achieving Stable Engine Operation of Gasoline Compression Ignition Using 87 AKI Gasoline Down to Idle. *SAE 2015 World Congress & Exhibition.* Detroit, United States, A21-23 April. Warrendale: SAE International.

[50] Pinazzi P.M, and F. Foucher. 2017. Influence of injection parameters, ozone seeding and residual NO on a Gasoline Compression Ignition (GCI) engine at low load. *Proceedings of the Combustion Institute* 36(3): 3659-3668.

[51] Pinazzi P.M. and F. Foucher. 2017. Potential of Ozone to Enable Low Load Operations of a Gasoline Compression Ignition (GCI) Engine. *WCX™ 17: SAE World Congress Experience.* Detroit, United States, 4-6 April. Warrendale: SAE International.

[52] Chuahy F.D.F., Moses-DeBusk M., Curran S.J., Storey J.M.E., and Wagnon S.W., 2021. The effects of distillation characteristics and aromatic content on low-load gasoline compression ignition (GCI) performance and soot emissions in a multi-cylinder engine. *Fuel* 299: 120893.