energies

Review

A Review of Gasoline Compression Ignition: A Promising Technology Potentially Fueled with Mixtures of Gasoline and Biodiesel to Meet Future Engine Efficiency and Emission Targets

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Abstract: Efforts have been made to develop efficient and alternative powertrains for internal combustion engines including combustion at low-temperature (LTC) concepts. LTC has been widely studied as a novel combustion mode that offers the possibility to minimize both nitrogen oxide (NOx) and particulate matter (PM) via enhanced air-fuel mixing and intake charge dilution, resulting in lower peak combustion temperatures. Gasoline compression ignition (GCI) is a new ignition method related to the extensive classification of combustion at low-temperature approaches. In this method of ignition, a fuel with high evaporation characteristics and low autoignition sensitivity, for instance gasoline, is burned in a high pressure process. Despite many research efforts, there are still many challenges related with GCI performance for compression ignition (CI) engines. Unstable combustion for idle- to low-load operation was observed because of the low reactivity characteristics of gasoline, and this will affect the efficiency and emissions of the engine. This paper contributes a detailed review of several topics associated with GCI engines and the effort to improve its efficiency and emissions, including its potential when using gasoline-biodiesel blends. Some recommendations are proposed to encourage GCI engines improvement and development in the near future.

Keywords: GCI; biodiesel; diesel; combustion; emission

1. Introduction

Energy savings, emission reduction, environmental friendliness and sustainable energy supplies are issues that attract much current attention. Investment in the research and development of alternative fuels and energy resources is growing rapidly at both national and international levels. The focus on the future energy supply is stimulated by anxieties associated with fossil fuel reserves. Global energy consumption forecasts continue to predict increasing request for liquid hydrocarbon fuels next shortly by internal combustion (IC) engines because these fuels are abundant, cheap and convenient. However, large-scale and extensive use of fossil fuels results in two bad situations: oil reserve depletion and environmental deterioration in the form of air pollution, increase in the average global temperature manifested as global warming, and climate change [1]. Therefore, it is important to promote and develop novel engine technologies and combustion strategies that focus on high efficiency and clean internal combustion engines.

Several attempts have been made to promote alternative and efficient powertrains for IC engines, including the combustion at low temperature (LTC) concept. LTC has been widely studied as a novel combustion mode, which offers the possibility to reduce both nitrogen oxide and particulate matter via enhanced air-fuel mixing and intake charge dilution resulting in lower peak combustion temperatures [2,3]. Compression ignition of gasoline (GCI) is a new combustion concept in the extensive classification of combustion at low-temperature approaches. For this new ignition type, a hydrocarbon fuel that has high evaporation property and less sensitivity to autoignition, for example gasoline, is burned under high pressure conditions [4–9]. Compression ignition of gasoline was first suggested by Kalghatgi to take advantage of the benefits of the high vapor and high autoignition of petroleum gasoline-like fuel and the high ratio of compression (CR) of CI engines to obtain maximum performance and near to zero emissions at the same time [4]. However, the lubricity of market gasoline is not adequate to protect today's fuel injection components, so either the engine components must become more robust or fuel lubricity additives will be needed. Furthermore, the major challenge for GCI is the very small cetane value of gasoline that is usually estimated to be no higher than about 15. This low value leads to long ignition delays and misfires. Therefore, the utilization of gasoline-diesel blends was suggested in engine ignition strategies. Besides the lengthened autoignition, their altered physical characteristics may promisingly influence the injection of fuel and characteristics of the jet spray, that are equally crucial for homogeneous mixture of fuel-air configuration and the combustion inside the cylinder of engine [10,11]. Later on, a certain portion of biodiesel was added to the gasoline fuel to achieve fuel properties that are appropriate for GCI engines and can overcome the autoignition problems observed in gasoline [12].

Despite many research efforts, many challenges related to GCI operation for CI engines still exist. Gasoline shows low reactivity characteristics, leading to unstable combustion for idle- to low-load operation, which will affect the efficiency and emissions of the CI engine operation. The efficiency of a GCI engine is estimated to be roughly equal that of a diesel engine and the emissions should be better than those of an SI engine. This research project deals with improving the efficiency and emission behaviors of CI engines using GCI mode and gasoline-biodiesel blend fuels. Understanding the main properties of fuel and quantifying the influences of several parameters on CI engines on compression ignition of gasoline mode, fueled with a biodiesel blended in gasoline are important for speeding up the contributions and theory to realize the utilization of gasoline in diesel engines and biofuels in the transportation area. Therefore, the aim of this paper is to contribute a detailed review of several topics associated with GCI engines and the efforts made to improve their efficiency and emissions, including their potential when using gasoline-biodiesel blends. Some recommendations are proposed to encourage GCI engine improvements and development in the near future.

2. Gasoline-Biodiesel Blends as Substitute Fuels for CI Engines

Gasoline with high octane number usually has high vaporization characteristics and is very difficult to ignite, and thus is called low reactivity fuel [13]. Spark ignition (SI) or gasoline engines are engines that are suitable for this gasoline fuel. However, a big issue of this fuel implementation in SI engines is the knocking phenomenon. This phenomenon allows gasoline engine to operate only at a low ratio of compression around 8 to 11, which is a limitation of the SI engine. Due to the low compression ratio, the limitation of gasoline engines is that they always display small efficiency. Furthermore, the gasoline engine application usually requires spark plugs to give a spark firing at the maximum of the stroke of compression as the trigger of combustion. Lastly, NOx emissions will be a final product because gasoline engines are usually operated with almost-stoichiometric mixtures which require high-temperature combustion [14].

Biodiesel is a substitute fuel for CI engines. It is a chemically modified biofuel made from either animal fats or vegetable oils. According to the ASTM D6751 biodiesel standard, biodiesel can be described as a "fuel containing monoalkyl esters of long-chain-fatty-acids processed from fats of animal or oils of vegetable, named B100". Biodiesel can be produced from many kind of seeds and crop plants, for example poppy seed, maize seed, camelina seed, seed of pumpkin, castor, grape, pea, beechnut, lupin, linseed, chestnut, rapeseed, peanut, olive, soybean, hemp, seed of sunflower, palm, Shea butter, and cottonseed [15,16]. Biodiesel is required to have the same chemical and physical features as diesel fuel. The biodiesel standards and properties of biodiesel around the globe are briefly presented in Table 1 [17], while, the superior features or deficiencies of biodiesel compared to diesel or petroleum fuels are as follows [17]:

Superiority of biodiesel compared to diesel fuel:

- Biodiesel is more portable, available and renewable.
- Emissions such as CO, CO_2, PM, SO_2, and HC from biodiesel are lower compared to petroleum-based diesel fuel.
- It is easier and faster to produce biodiesel than diesel petroleum-based fuel.
- The cetane value of biodiesel is higher than 100 that can results in better performance of CI engines than petroleum diesel fuel.
- Biodiesel's lubricity is better compared to petroleum-based diesel fuel which can reduce engine maintenance and improve the engine lifetime.
- Different from conventional diesel, biodiesel can be used without additional lubricants because of its purity and the clarity.
- Biodiesel can be used to solve energy security problems and has great potential to stimulate rural development and sustainability.
- Biodiesel can be obtained without mining, transporting, or refining activities like petroleum diesel fuel.
- Biodiesel can be produced locally, thus being cheaper than petroleum diesel fuel.
- The aromatic content, flash point, sulfur content, and biodegradability of biodiesel are better excellent than those of petroleum diesel fuel.
- Biodiesel is safer, much more non-toxic, and more biodegradable compared to petroleum-based diesel fuel.
- Biodiesel is non-flammable, however it has higher combustion efficiency because of its huge oxygen fraction if compared to petroleum diesel.
- Biodiesel can produce low emissions, less visible smoke, and smalles amounts of noxious fumes and odors.
- Blends of up to 20% biodiesel can be run without any modification of engines.

Table 1. Biodiesel standards and properties of biodiesel [Reprinted from Procedia Engineering, Vol. 56, Masjuki Hj. Hassan, Md. Abul Kalam, An Overview of Biofuel as a Renewable Energy Source: Development and Challenges, Copyrights (2013); with permission from Elsevier].

Properties (units)	Malaysia	Indonesia Republic of	Thailand	US	European Union	Brazil
		SNI	E 14214	ASTM D6751	E 14214	ANP 42
Minimum flash point (°C)	182	100	120	130	120	100
Viscosity at 40 °C (cSt)	4.415	2.3–6.0	3.5–5	1.9–6	3.5–5	-
Maximum of sulphated ash (%-mass)	0.01	0.02	0.02	0.02	0.02	0.02
Minimum of sulphur (%-mass)	0.001	0.001	0.001	0.001	0.001	-
Maximum of cloud point (°C)	15.2	18	-	-	-	-
Classification of copper corrosion (3 h, 50 °C)	1	3	1	3	1	1
Minimum of cetane number	-	51	51	47	51	-
Maximum of sediment and water content (volume %)	0.05	0.05	-	0.05	-	0.05
Maximum of CCR 100% (%-mass)	-	-	0.3	0.05	-	0.1
Neutralization value (mg, KOH/gm)	-	-	-	0.05	0.05	0.08
Maximum Free glycerin (%-mass)	0.01	0.02	0.02	0.02	0.02	0.02
Maximum Total glycerin (%-mass)	0.01	0.24	0.25	0.24	0.25	0.38
Maximum Phosphorus (%-mass)	-	10	0.001	0.001	0.001	-
Maximum distillation temperature (°C)	-	360	-	360	-	360
Oxidation stability (h)	-	-	6	3	6	6

Deficiencies of biodiesel compared to petroleum diesel fuel:

- It produces higher emissions of NOx than petroleum diesel fuel.
- Biodiesel has cold weather starting problems due to the higher cloud and pour point causing fuel freezing.
- Biodiesel is naturally corrosive if exposed to brass and copper.
- Biodiesel has around 11 to 17 times higher viscosity than diesel. Furthermore, pumping, atomization in the injector systems and combustion problems commonly happen in diesel engines due to the larger chemical structure and molecular mass of biodiesel than diesel.
- The engine speed and power of the diesel engine is lower when utilizing biodiesel.
- Biodiesel produces deposits in injectors, on the pistons, on the combustion chamber walls, and on the head of engines.
- Deposit formation inside injector and on rings and filter and line plugging will happen due to the gumming and sticking which are promoted by its high viscosity in long term operation using biodiesel.
- Biodiesel is incompatible with petroleum-based engine lubricating oils.
- Excessive engine wear can be caused by biodiesel.
- The cost-competitiveness of biodiesel cannot be compared with petroleum gasoline or diesel.

LTC is a famous combustion concept in CI engines, which proposes the possibility to reduce nitrogen oxide and particulate matter (PM). By using suitable modification of fuel properties, by the addition of gasoline [10], which has higher vaporization characteristics and lower cetane number is possible to achieve LTC in a CI engine with GCI mode [18,19]. The more retarded autoignition timing of gasoline because of its high octane number leads to adequate air-fuel mixing, thus, the enhanced thermal efficiency improves the combustion pre-mixing, resulting in decreased soot and NOx values [18]. The high thermal efficiency, low soot and NOx emissions, and low combustion temperature compared to gasoline engines are the main benefits of GCI engines [20]. However, the required high intake temperature, low lubricity, and requirement for a high ratio of compression like a diesel engine are the deficiencies of GCI engines. Biodiesel has high possibilities to solve many issues in GCI engine implementations when blended with gasoline, such as the low lubricity. Furthermore, because of the high content of oxygen in biodiesel, perfect combustion may also be achieved [21].

3. Challenges and Opportunities in GCI Engine Research

The common emission problems in CI engines are NOx and particulate matter (PM) formation [22,23]. Serious environmental and health problems might be caused by air pollution which is contributed by these emissions. Advanced technologies such as subsequent systems or after- treatment systems are being promoted to solve and control these engine emissions. However, these technologies are complicated, expensive, and reduce the primary benefit of CI engines. Additionally, emission regulations, particularly for diesel engine vehicles, are getting to be tighter everywhere throughout the globe. Therefore, researchers in the engine field have a motivation to study the necessity of implementation of high vapor fuels, for instance gasoline and other substitute fuels, for diesel engine combustion operations that afford high performance but near-zero exhaust emissions. A sustainable substitute fuel that is very suitable for diesel engines is biodiesel. Various renewable resources can be used to make biodiesel fuel [24,25]. Furthermore, it has proven that because the oxygen fraction in biodiesel has a main function of reducing soot formation during the combustion process [26], biodiesel has excellent benefits in reducing the soot emissions of CI engines [27,28].

The efficiency of diesel engines or diesel engines are much higher than that of gasoline engines, according to some considerable analysis [29]. First, CI engines can be run better at higher compression ratios because do not suffer deterioration from knocking at high loads compared to SI engines. Second, part load operation can be carried out in CI engines by reducing the injected fuel, instead of managing the air-mass compressed in the chamber of combustion. Third, performance near to an ideal cycle efficiency can be achieved due to the fact only air is trapped during the compression movement in a CI engine, rather than an air-fuel mixture. However, the huge emissions, especially soot/particulate matter/smoke and NOx, that are difficult to reduce by using after-treatments, are always produced by CI engines using diesel fuel. On the contrary, lower engine efficiency and lower exhaust emissions, especially nitrogen oxide and particulate matter are produced by SI engines using a petroleum-based gasoline fuel. Therefore, based on these realities, it is necessary to apply an advance combustion strategy to obtain an efficiency as high as an CI engine and emit less emissions like an SI engine [4,30]. Nowadays, consideration is being given to the GCI engine as the LTC method with the most potential because high thermal efficiency and low emission behavior can be produced using this concept [20,31–36]. GCI combustion is more practical to solve the issues of the complexity of combustion controllability than other LTC concepts for CI engines, for example premixed-charge-CI (PCCI) and homogeneous-charge-CI (HCCI), even though these concepts also offer interesting ignition phenomena under homogeneously lean air-fuel mixing conditions [11,12,37–40].

Engine experiments are very important for understanding the real phenomena of the combustion process and emission behaviors of an IC engine. However, these are usually costly and complicated. Therefore, only a few researchers have included engine experiments in their studies. An extensive search of the literature showed that there are only a few references for experimental studies of GCI engines, and studies on GCIs fueled with gasoline-biodiesel blends are even rarer. Most of the studies use simulations and numerical methods. Thus, sequential and complementary experimental studies are needed to achieve a better understanding of the process of combustion inside the cylinder and emission behaviors of GCI engines fueled using blend of biodiesel in gasoline fuel.

4. LTC Concept

The objective of advanced engine operating strategies is to increase the efficiency and decrease exhaust emissions in IC engines. The primary research focus is the development of LTC concepts. LTC methods offer the possibility to reduce both nitrogen oxide and particulate matter (PM) via enhanced air-fuel mixing and intake charge dilution, resulting in lower peak combustion temperatures [41]. Depending on the air and mixing of fuel distribution and temperatures of combustion in the combustion chamber at various operating points, there exist regions of excessive soot or NOx formation (also referred to as soot or NOx 'islands') [42]. The soot or NOx islands and LTC concept derivatives (HCCI) are shown in Figure 1 [2].

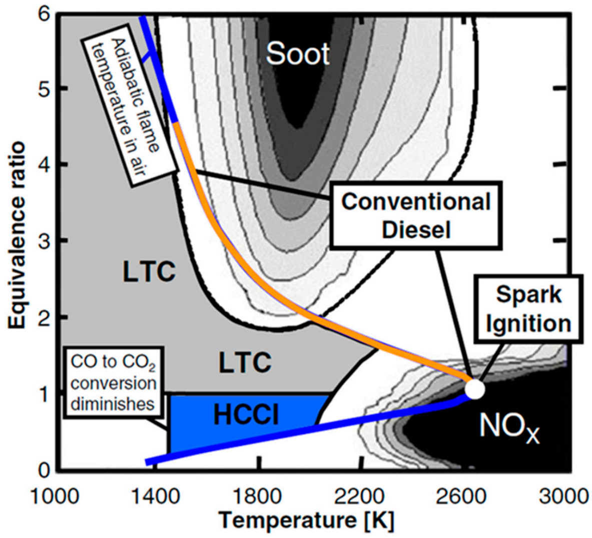


Figure 1. Soot or NOx islands, LTC and conventional CI combustion regimes in ϕ-T space [Reprinted from Proceedings of the Combustion Institute, Vol. 32, John E. Dec, Advanced compression-ignition engines—understanding the incylinder processes, Copyrights (2009); with permission from Elsevier].

According to Loeper et al. [42], reducing soot and NOx emissions simultaneously in conventional diesel combustion has long proved challenging due to the operating points that exist within "islands" of soot or NOx formation, as shown in Figure 1. This duality of achieving either low NOx or soot formation, but not both, is attributed to as the soot-nitrogen oxide trade-off. Low NOx formation rates can be achieved by reducing the combustion temperature, but this is traditionally accompanied by either high soot formation (due to poor air utilization and/or incomplete combustion) or significant restrictions in engine load (or power). Of course, soot formation can be reduced with superior air utilization, but this results in higher combustion temperatures and NOx formation rates. These compromises in conventional diesel combustion have spurred engine researchers to seek combustion strategies (e.g., LTC, HCCI, etc.) that avoid the NOx/soot islands altogether.

HCCI combustion, which operates on the similar basic fundamentals as a 4-stroke IC engine and employs the main components of gasoline and diesel engines is the most famous type of LTC concept, nowadays [43]. HCCI is the pioneer of one type of LTC, and is probably the most extensively researched [41]. In the HCCI concept, a uniform mixture of air and fuel is compressed in the engine cylinder until its pressure and temperature reach auto ignition. The clean soot characteristics of traditional fully-mixing gasoline engine combustion, homogeneous, high efficiencies (obtained by lean and unthrottled conditions) which is usual characteristics of diesel engine combustion, are combined in the HCCI method. Through the high amounts of mixture with air and/or fuels HCCI that keeps the NOx emissions at a low level, HCCI can achieve the lowest soot emissions and NOx at high efficiencies equal to, or higher than, traditional CI combustion because of these mentioned factors [2]. However, because of the minimum of straight control through the beginning and HRR, HCCI is only can be achieved over a limited range by operating a part-load area [44]. A preferable understanding of the principal combustion processes is needed to provide control through HR in HCCI. A more practical LTC strategy that can solve the problems of HCCI engines is GCI, in which a more difficult auto ignition fuel (i.e., gasoline) is directly injected into the chamber using a fueling system (common rail) in a diesel engine [4].

Even though the LTC concept is radically different from the conventional SI combustion or CI diffusion combustion concepts, LTC technology offers excellent benefits in terms of simultaneous reduction of both NOx and particulate matter or soot in addition to reducing specific fuel consumption and offering the flexibility of using various fuels. Furthermore, the main requirement of the LTC concept is the availability of a homogeneous fuel–air mixture before the start of combustion. This requirement is potentially fulfilled by using CI engines fueled with gasoline. The gasoline fuel can be injected directly into the cylinder with an early injection strategy, pilot and main injection, and also the application of EGR and intake boosting. With the naturally volatile characteristics of the gasoline, the gasoline can be mixed with air nearly homogenously before the combustion as required by the LTC concept. It cannot be denied that as long as the combustion in GCI concept is by auto ignition, the controlling ignition timing and heat release rate (HRR) are the main problems and challenges to be managed before LTC is achieved. However, since the combustion occurrs in the CI engines with gasoline fuel, the low temperature regime, NTC, and high temperature regime from the typical HRR curve of CI engines combustion can be predicted. Thus, GCI engines are relevant to the LTC concept.

5. GCI Engines and CI Engines with Gasoline Fuel

5.1. GCI Engines

To provide a review of previous research works associated to GCI engines, utilization of gasoline-biodiesel blends as internal combustion engine fuel and experimental studies of GCI combustion are the purposes of this section. This section also provides a review of other relevant research studies. To offer a perception into how previous research works have laid the groundwork for further works the review is organized chronologically. The new research efforts can be suitably tailored to correlate with the current body of literature because the review is detailed.

Gasoline compression ignition is a novel concept of ignition that belongs to the wider classification of LTC approaches. In this method, a poor reactivity fuel with high volatility, for example gasoline, is burned perfectly by using pressurized conditions [4,20,31,35,45,46]. The throttle-less, lean, and low-temperature combustion operation can lead GCI to achieve the same or better efficiencies than CI engines. Very low soot (because of the excellent mixing characteristics of gasoline) and less NOx emissions (because of the LTC and absence of flames) compared to conventional CI combustion, can also be emitted by this combustion strategy. Based on a reactivity stratification of fuel, it can be explained that the combustion in GCI is a result of sequential autoignition [47], without significant flame propagation. The aim of GCI is to manage the ignition delay period by managing stratification of air-fuel equivalence ratio concentrations inside the combustion chamber. A highly volatile and poor reactivity fuel (e.g., gasoline) is burned solely by compression (without any support from a spark plug) to prevent propagating flames and control the combustion temperatures and NOx emissions. This has been designated in the literature by various names/titles and terms, for example gasoline-direct-compression-ignition (GDCI), and gasoline-direct-injection-compression-ignition (GDICI). Throughout this study we will refer to this concept as GCI.

Compression ignition of gasoline was first studied by Kalghatgi [4] to take advantage of the benefits of the high vapor characteristics and high auto-burning resistance of petroleum gasoline fuel and the high ratio of compression of CI engines to simultaneously achieve almost-zero emissions and excellent efficiency. The GCI fuels can be categorized into two groups, low octane number fuels and high-octane number fuels [48]. A high-octane number fuel commonly refers to petroleum gasoline fuel with an octane number bigger than 90. Fuels with low octane number have higher auto burning and can be used in broader operating ranges with smaller load if compared with high octane fuels. The common approach to get a low octane number fuel is by blending gasoline and diesel, and there is also blending with biodiesel, bioethanol and other cetane improvers [11,12,49,50].

Based on Cracknell et al. [31], the potential advantages of fueling CI engines with gasoline in GCI combustion mode are as follows: First, CI engines have higher efficiency over SI/gasoline engines and have the possibility to use a broader fuels range. Second, the ability of GCI engine concepts to use available market gasoline would allow these concepts to enter engine applications quickly without fuel constraints. Third, more gasoline consumption in passenger cars would help to rebalance the gasoline/diesel fuel demand in refineries and reduce GHG emissions from the fuel supply in several countries. Fourth, a successful GCI vehicle could potentially compete in predominantly gasoline markets in other parts of the world.

5.2. CI Engines with Gasoline Fuel

Because of the high octane number of 100% gasoline fuel and its difficulty for auto-burning at the low level of temperatures of mixtures common in low-load conditions, GCI combustion faces challenges under low load operation. Thus, several methods are required to obtain optimal combustion and good exhaust emissions. The focus of this work is to improve the emission behaviors and efficiency of CI engines fueled with gasoline-biodiesel blends using GCI mode. We performed a literature study before attempts were made to enhance the efficiency and emission behaviors of CI engines fueled with gasoline-biodiesel blends. This study gives an overview of currently available research regarding the use of gasoline in CI engines using several combustion strategies.

Kalghatgi et al. [4] investigated the influence of fuel quality for its auto-burning characteristics among four fuels ranging from diesel towards gasoline fuels on combustion process at two different EGR levels and inlet pressures. The CI engine can be operated without problems using gasoline by single injection near TDC, although it difficult to operated with too early fuel injection in the HCCI combustion because of auto ignition failure or because of excessive heat release. The results of Kalghatgi et al. [4] showed the possibility of using the autoignition resistance of fuels with higher octane/lower cetane to obtain high IMEP with a low NOx, low smoke combustion system. In another study, Kalghatgi et al. [45], improved the GCI concept by proposing partially pre-mixed auto-burning of gasoline to achieve better smoke and better NOx at high load in a CI engine; they also compared this with a diesel fuel. The results indicated that pilot injection with gasoline decreases the peak of HRR for an adjusted IMEP, and allows HR to appear retarded with a small cycle variation compared to one-time injection. However, there are still challenges related to further improvements that may be realized by various EGR ratio schemes and boosting intake pressure and by optimization of the mixture preparation and strategy of injection (for example multiple injections), and the design of injectors (for example many holes injectors) [45].

Weall and Collings [51] conducted a study in a multi-cylinder, light duty type CI engine, using PPC mode fueled using a gasoline-diesel compound. Their results show that an upward content of gasoline decreased smoke emissions at higher working loads by an upward premixing of the in charge obtained from an increase in auto burning timing and higher vapor characteristics of the fuel. The results of Weall and Colling's work [51] confirmed that a blending of fuel features indicates higher vapor characteristics and prolonged auto ignition timing would widen the low emission-operating regime, but combustion stability at low operating loads must be considered [51]. Furthermore, engine idling was possible with a 50% of gasoline ratio test fuel, but cold start issues could emerge as a significant problem with such combustion regimes when using alternative fuels with present technology diesel cold start systems.

Experiments on the effects of gasoline by the port injection method have been conducted in a 1-cylinder CI engine with direct injection type by Sahin et al. [52]. The gasoline fuel was introduced through intake port using a carburetor, and there no other changes to the engine specifications are needed. The results showed that a 4 to 9% increase of power output resulted and efficiency was increased by around 1.5 to 4% and fuel burning reduced by about 1.5 to 4% due to gasoline volatilization. However, the exhaust gas emissions from the engine were not analyzed. Meanwhile, a parametric study of a CI engine running with gasoline was conducted in numerical simulation by Ra et al. [6]. The results indicated that the predictions concerning high pressure direct injection gasoline engine combustion and its emissions agreed with experimental results for various parameters. For the similar CA50, gasoline will have a much longer CA10 compared to diesel fuel; thus, nitrogen oxide and PM emissions were greatly decreased compared to the similar cases of diesel. The results also described that optimal injection timing with lowest UHC and CO emissions was produced by accelerating the timing of main injection in the combustion of gasoline. However, the timing of main injection has to be chosen as an balance between increasing of PRR levels and emissions reduction.

Another type of in-cylinder mixing fuel of diesel and gasoline has been studied by Curran et al. [40], who introduced gasoline in a port-fuel-injection system. The results from this study showed that the temperature of the intake charge has a high effect on cylinder PRR, while the thermal efficiency increased simultaneously with NOx and PM emission reductions for around 90%. However, the indicated thermal efficiency for the many-cylinder tests were lower than estimated from simulation and 1-cylinder measurements. The smaller indicated thermal efficiency of the experimental result compared to the modeling measurements showed that an improvement of cylinder-to-cylinder regulation and more optimization in dual-fuel mode were needed.

The emission behaviors of a CI engine fueled with in-cylinder dieseline blends has been studied by Prikhodko et al. [39]. The results from this work showed that 87% and 99% reductions in NOx and PM emissions were achieved in combustion of dual-fuel RCCI, and the thermal efficiency was increased by 1.7% as compared to combustion of normal diesel. However, CO, aldehyde, HC, and ketone emissions increased significantly for combustion of dual-fuel RCCI compared to conventional diesel and PCCI combustion of diesel. Shi and Reitz conducted a study on optimization of a heavy-duty CI engine running under middle-load and high-load operation conditions using petroleum diesel, petroleum gasoline, and an ethanol blend (E10) [19]. The study indicated that identical-gasoline fuels are potentially useful for heavy-duty CI engines with an optimized injection system because of their decreased soot and emissions of NOx and lower fuel consumption compared to traditional diesel petroleum-based fuels. However, the high PRR corresponding to the PPC of gasoline-like fuels might be a restriction for high load operation and a challenge for small-load operation.

Several tests were conducted in 2-single-cylinder engines, using a total of three various engine settings to show the advantages of using gasoline from 80 to 69 RON in a heavy-duty type CI engine [53]. The authors of this research concluded that if in the constant engine setting gasoline of around 70 octane is the most suitable for this combustion, and if higher octane gasoline is used in partial premix combustion, either a variable compression ratio or a cylinder heater should be used to operate under lower-load conditions. A blend of 20% gasoline and 80% diesel named G20, was tested in a 1-cylinder optical CI engine with two different pressures of injection set at 700 and 1400 bar, and injection timings from 11 °CA BTDC to 5 °CA ATDC [54]. The results showed that the G20 at retarded timing of injection and 50% EGR increased the auto ignition timing enabling the operation with retarded injection timing with premixed fuel in partial LTC mode where the fuel is fully injected prior to the auto ignition happening. In this method, great reductions of nitrogen oxide and smoke were achieved with deterioration of efficiency.

Ra et al. [7] conducted a study of a GDICI in the LTC method. The results exhibited good agreement between the modeling and experiments. Furthermore, because of the high vapor characteristics and low number of cetane of gasoline incorporated with the decreased temperature of combustion due to EGR application, either NOx or PM emissions could be decreased up to 100 mg/kg-f while experimental gross isfc was controlled at around 0.18 kg/kw-h. Zhang et al. [55]. conducted another PPCI study of dieseline in a CI engine. The results showed that diesel-gasoline had significant benefits as a combustion fuel of PPCI for emission minimizing purposes. It was also found that the total particle number concentration could be decreased by 90% by mixing 50% gasoline in the diesel, in addition, low NOx and higher thermal efficiency of approximately 30% were controlled for all variations of the loads. There is also another study on a DICI engine fueled with gasoline in the LTC mode with triple-pulse injection conducted by Ra et al. [8]. They showed that the stability of combustion and peak PRR might be adjusted by the pulse number two, while the pulse number three can be utilized to manage the engine load. Furthermore, by using the triple-injection strategy along with EGR, either NOx or PM could be decreased up to around 100 mg/kg-f, while obtaining isfc at around 0.173 kg/kW-h.

An experimental study has been done to compare the emission characteristics and combustion process of the late and early injection for highly premixed charge combustion (L-HPCC and E-HPCC, respectively) modes and the mixed fuel LTC mode [18]. Combustion with the L-HPCC and LTC may occur with local regions that are close to stoichiometric because of fuel stratification. Hence, they have relatively high NOx emissions, which could be lowered with increasing EGR rates. The soot emissions for the three modes of combustion are lower and below the Euro 6 regulation limits. The HC emissions of the E-HPCC and LHPCC regime are higher than those of the LTC because the premixed mixture of gasoline was trapped in the crevice area.

Another experimental investigation of a GCI engine has been conducted by Loeper et al. [46], to study the light to medium load operating sensitivity. The results revealed that input parameters can be used to reduce nitrogen oxide emissions below 600 g/kg-f with appropriate stability of combustion which is COV of IMEP below 3%, through a large intake temperature range. In addition, optimization refers to the efficiency of combustion and either CO or UHC emissions could be realized with the input parameter controllability.

Adams et al. [12] investigated the influences of biodiesel fraction in gasoline on GCI mode by injecting the fuel into the engine chamber directly. The main recommendation of this work is that the temperature of intake demands were decreased by 288 K and 303 K for the 5% and 10% biodiesel contents, respectively, compared to pure gasoline at a similar CA50. Biodiesel content at 5% and 10% significantly reduced CA10 and therefore advanced the CA50 compared with operation on pure gasoline. Pure gasoline produce higher average bulk gas temperatures resulting in higher NOx emissions as well as lower unburned hydrocarbon and carbon monoxide. Oxidations of carbon monoxide were not improved by the increased oxygen content of the biodiesel blends. Another experimental study was done to analyze the performance, combustion noise and emissions in PCCI regime using dieseline fuel [11]. The results showed that as the gasoline content increases, the CA10 increases, resulting in higher mixing time between the close of injection and the auto burning timing, thus, lower equivalence ratios are produced in local areas, and soot emissions are lowered. Finally, the performances and combustion noise are reduced. However, NOx emissions are a little bit increased.

A novel combustion method called multiple premixed compression ignition or MPCI was suggested by Yang [56]. The results revealed that the RON 66 MPCI regime decreased NO, CO, and soot, increasing thermal efficiency, but also increasing THC emissions compared to conventional CI engines. However, it is difficult to obtain the similar performance for RON 76 and RON 86 because of the lower auto-ignition ability compared to RON 66. Other spray and combustion phenomena of dieseline were investigated in a DI common rail CI engine [57]. The results showed that the combustion of gasoline produced higher HC, CO, and NOx but emitted less soot than combustion of pure diesel. However, the PCCI with early injection application significantly reduced emissions of nitrogen oxide compared to gasoline ignition.

Experimental and simulation studies of swirl effects at the intake port of a GCI engine have been carried out by Loeper [42]. A lowering in swirl rate from 2.2 to 1.5 caused a 6 °CA earlier combustion phasing, while rising swirl rate from 2.2 to 3.5 leads in a 2 °CA delay of combustion phasing. This earlier combustion phasing at the 1.5 swirl rate was followed by a huge increase of NOx emissions from 200 to 1600 g/kg-f. Another study testing various dieseline ratios in a CI engine was carried out by Zhang et al. [14]. The results indicated that the total PM of G50 was decreased by up to 50% and 90%, and the count median diameter was reduced by 25% and 75% at small and medium loads, respectively. Then, the G50 produced the minimum smoke 0.5 FSN for all tested load operations, while, compared with the diesel, NOx emissions of G50 were reduced by 50% at low speed, and increased by 20% at medium speed. Furthermore, the diesel-gasoline produces lower PRR and HRR peaks at low speeds, and it extended the CA10 by up to 7 °CA compared to diesel combustion.

One more characterization of the CA10 for a CI engine fueled with dieseline was conducted by Thoo et al. [58]. Higher gasoline ratio delayed the beginning of fuel injection up to 3 °CA, because of the changes in physical characteristics. The change in timing of injection influenced CA50, but did not affect CA10 directly. An analysis of the stability of GCI engine mode was conducted on idle operating speed and load operating condition on a many-cylinder CI engine using a gasoline with 87 index of anti-knock (AKI) by Kolodziej et al. [59]. Although hot EGR was successfully able to significantly increase the intake temperature, the simultaneous reduction of in-cylinder trapped mass and slight reduction of charge oxygen concentration had a more significant effect on reducing the mixture reactivity.

Three low octane number fuels: naphtha, dieseline G70D30, and the gasoline-*n*-heptane blend G70H30 were characterized for their combustion and emission phenomenon in MPCI regime by Wang et al. [60]. The results showed that the CA10 of the gasoline was longer with a higher pressure of injection. Then, the emissions of soot decreased at increased pressure of injection with a deterioration of increased CO and HC. Another experimental work on fuel consumption and exhaust emissions of DI premixed combustion engines using dieseline was conducted by Du et al. [61]. The results indicated that the CA10 was retarded and resulted in reduction of smoke. However, too high gasoline ratio might have the worst fuel economy.

Yang and Chou [62] numerically studied the engine performance and emission behaviors of a DI CI engine fueled with dieseline. The results showed that the CA10 was retarded by increasing of gasoline content. The 100% diesel operation achieved higher performance at low load. On the contrary, at middle and high loads of blended fuels, better performance could be realized, but slightly higher NOx emissions also occurred. Another work concerned the experimental study of the influence of fuel injection strategies on LTC fueled with gasoline on a 1-cylinder diesel engine was conducted by Yang et al. [63]. The results showed that the double-injection mode enabled expanding the high-efficiency and low emission combustion area, with higher soot, THC, and CO emissions at high loads and a little decrease in the efficiency of combustion and thermal efficiency. However, peak PRR and soot emissions were the predominant constraints on the load expansion of gasoline LTC, and they are related to their trade-off relationship.

Kodavasal [35] studied the effects of swirl ratio, injection parameters, and boost on GCI engine at idle and small-load operations by closed-cycle CFD simulations with an 87 anti-knock index fuel. The results showed that smaller nozzle angles lead to more reactivity or easier to ignite fuel and are appropriate over a larger range of injection timings. However, for low-load operation, smaller injection pressures did not improve ignitability, and this may be because of the reduced chemical residence time due to longer injection periods. Huang et al. [64] carried out an experimental study to investigate the process of combustion and the emissions behaviors of a many-cylinder diesel engine using neat diesel, dieseline, diesel mixed with *n*-butanol, and dieseline mixed with *n*-butanol blends. The results revealed that the addition of gasoline or *n*-butanol increased BSFC and NOx but decreased soot. The most interesting finding in this research was that the emissions of D70B30 achieved the optimum amounts at approximately 25%EGR. Another set of numerical simulation and experiments to enhance the efficiency of fuel in CI engines using dieseline and a technology of optimization have been conducted by Lee et al. [65]. The results showed that the CA10-CA90 duration and the IMEP dropped as the gasoline ratio increased. The uniformity of the A/F mixture was improved because CA10 was retarded. The emissions of soot were reduced by a huge amount of up to 90% compared to 100% diesel operation. The NOx emissions of the dieseline were a little bit increased when the SOI was retarded near to TDC.

Experiments in a CI engine fueled with 100% diesel, gasoline-diesel (GD) blends, and gasoline-diesel-polyoxymethylene dimethyl ether (GDP) blends were done by Liu et al. [66]. The study showed that either GDP or GD have one-stage premixed HR. GDP had an earlier CA10, lower peak of PRR and COV-IMEP compared to GD. Furthermore, GD had smaller amounts of emissions of soot than neat diesel, while the blends of GDP had the lowest emissions of soot and indicated the best trade-off between nitrogen oxide-soot emissions. Another study of dieseline with MPCI was done on a light-duty 1-cylinder CI engine by Wang et al. [67]. Their results showed that dieseline can simultaneously reduce emissions of NOx and soot and also maintain or obtain a higher indicated thermal efficiency than combustion of diesel fuel. However, the emissions CO and HC were increased for the dieseline.

Yu et al. [48] conducted an experimental investigation on combustion of PPCI and MPCI fueled with five type of gasoline-like fuels: gasoline, gasoline mixed with ethylhexyl-nitrate blends (EHN), blends of dieseline, blends of gasoline and polyoxymethylene dimethyl ether (PODEn), and blends of dieselin-PODEn, designated as G, GE, GD, GP, GDP, respectively. The results indicated that the thermal efficiency in PPCI regime from the biggest to the smallest was GP, G, GDP, GE, and GD, while in MPCI regime was GP, GDP, GE, G, and GD. In PPCI regime, nitrogen oxide and emissions of soot were lower than 40 mg/kWh and 10 mg/kWh, respectively, fulfilling the Euro six emission standards. Meanwhile, nitrogen oxide emissions in MPCI regime were acceptable for Euro six. CFD closed-cycle simulations have been done by Kodavasal [47] on GCI combustion regime with a sector mesh to study the influences of model scenarios on the simulation results. PRR and HRRs are exceeding the values predicted by the simulation, as are nitrogen oxide, carbon monoxide, and hydrocarbon emissions. The exceeding predicted HRR and nitrogen oxide might be because of the good mixing assumption for the simulation of combustion.

The most comprehensive study about application of gasoline fuel in the CI engines was conducted by Reitz and Duraisamy using the RCCI combustion strategy [68]. However, RCCI is a little different from GCI combustion. RCCI involves blending a low reactivity fuel (gasoline) and a high reactivity fuel (diesel) using a dual fuel strategy which uses two types of fuel injection system with different injectors and separate fuel tanks. The first fuel system is for gasoline fuel with a port injection method, the second fuel system is for diesel fuel with a direct injection system. Meanwhile, GCI uses only one fuel system that is direct injection, and blends the two types of fuel in the fuel tank. GCI is simpler and easier in fuel system configuration and real application.

5.3. Potential Methods to Obtain High Efficiency and Low Emission Targets of CI Engines in GCI Modes

The literature review has revealed studies on CI engines fueled with gasoline and/or blended with other fuels running in GCI mode or a similar method. Significant progress in the GCI research field in both experimental works and simulation studies has been achieved. There are however still many areas that need further study due to the complexity of the CI engines, which operate in GCI combustion mode. The information on the combustion characteristics of CI engines when gasoline and GCI act as the main fuel and combustion mode, respectively, are still limited. An extensive review showed that most research dealt with gasoline and biodiesel as a fuel supplement/additive in CI engines.

In general, there is an apparent lack of experimental studies of CI engines fueled with gasoline-biodiesel blends. The characteristics of emissions, ignition, and combustion process of the dieseline blends that greatly influence the efficiency of CI engine are well understood, however, the ignition, combustion, efficiency and emission characteristics are not well understood in a CI engine in which gasoline-biodiesel fuel is used.

Fuel properties and formation play an important function in the combustion process. An experimental and simulation study on the gasoline-diesel blend mixing strategy inside the cylinder would be a good contribution to elucidate combustion in GCI engines. Some simulation results on combustion processes display good agreement with the experimental ones. However, many areas remain unaddressed by the previous simulation and experimental studies. Studies on gasoline-biodiesel blends as alternatives for CI engines are very rare (especially for experimental work). Combustion process and emissions analysis on GCI combustion fueled using gasoline-biodiesel blends based on experimental work would give a better foundation for efforts to enhance CI engine efficiency.

To fill these gaps, some sequential experimental and/or simulation works can be conducted to identify the important parameters and phenomena related to the combustion process and emission behaviors of a CI engine fueled with gasoline-biodiesel blends to improve its efficiency. The literature review above can provide guidance in arranging, planning and proposing an experimental procedure and hypothesis to reach high efficiency and low emissions targets for CI engines fueled with gasoline-biodiesel blends [67,69–98] A brief explanation on how to obtain the targets is summarized in the effect flowchart shown in Figure 2.

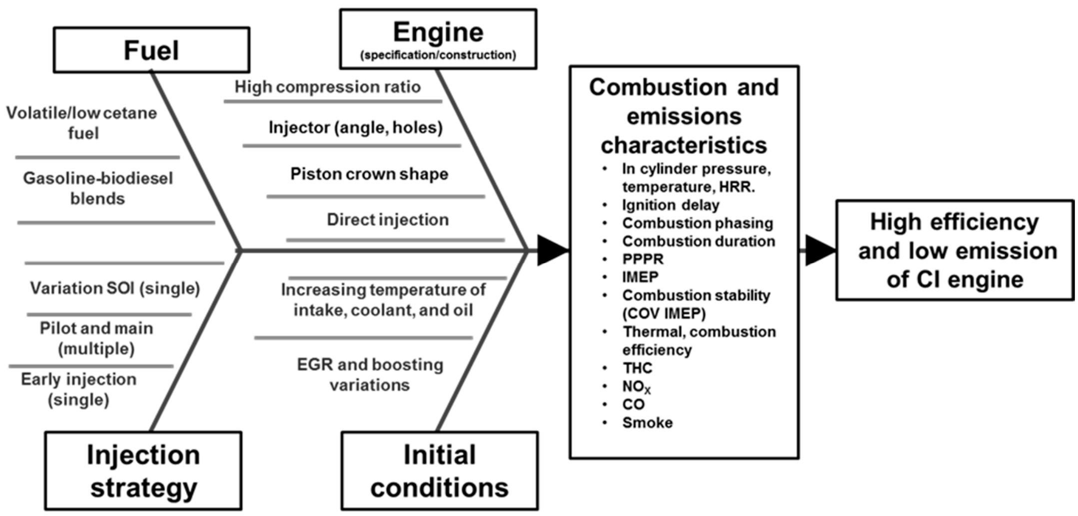


Figure 2. Flowchart of the potential strategies to obtain high efficiency and low emission CI engines fueled with gasoline-biodiesel blends.

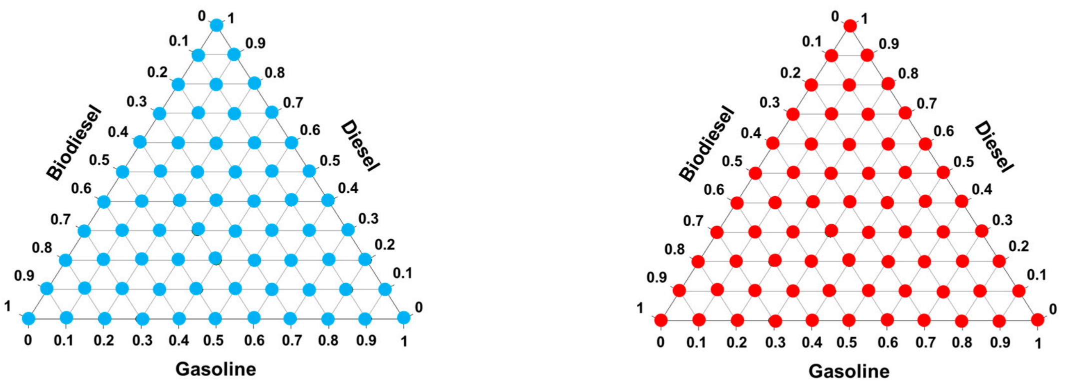
5.4. Studies on GCI Engines Fueled Using Gasoline and Biodiesel Blends

Since early 2014, the Smart Powertrain Laboratory at the University of Ulsan has conducted several studies, including experimental and simulation activities, for potentially blending gasoline fuel with certain concentrations of biodiesel to obtain good combustion process and behaviors of emissions in a CI engine. Our specific achievements are detailed in the following subsections.

5.4.1. Gasoline-Biodiesel Preparation and Properties during Storage

Blending biodiesel and gasoline is known to have stability issues because of large density difference. In the case of low quality of biodiesel which has a high water content the stability issue should be solved. As studied previously emulsions of water and fuel (oil-based) display many phenomena related to their stability [99–104]. Therefore, further study of the properties of the blends, especially their stability due to the large density difference between gasoline and biodiesel is necessary. Currently, the maximum suitable biodiesel blend in petroleum fuel in term of temperature properties is 20% [21]. Other researchers have suggested that a petroleum based fuel consisting of 25% biodiesel was indicated to be the best-suited blend for an engine without heating and without any engine modification [76]. Meanwhile, Tinprabath [77] reported that fuel blends with biodiesel below 5% do not affect the cold flow properties.

As long as fuel grade (very low and near to zero water content) biodiesel is used, gasoline-biodiesel blends can be prepared by a simply mixing or shaking process for about 2–10 min to produce homogeneous fuel blends, which then must be immediately used in the engine experiments to avoid fuel stratification [105]. However, the fuel stratification during storage must be analyzed to understand the characteristics of the blends in real applications. Thongchai and Lim [106] prepared gasoline-biodiesel blends from 5% to 20% of biodiesel content and analyzed the phase stability and the properties during storage. Usually, phase separation occurred at low temperatures and long periods of storage. As shown in Figure 3, the ternary phase diagram indicates that no phase separation occurred for all gasoline-biodiesel blend ratios even though they were stored at a low ambient temperature from 20 °C to 10 °C, around 1 h, and for a long period of time at 25 °C, for around 45 days [106]. Figure 4 shows the clear appearance of the gasoline-biodiesel blends without phase separation [106]. The physical properties of gasoline, biodiesel, diesel, and gasoline-biodiesel blends are presented in Table 2. Meanwhile, the explanation that indicates that a 5% biodiesel content in gasoline-biodiesel blends fulfills the lubricity requirements for CI engine fuel systems can be seen in Figure 5.



(**a**) (**b**)

Figure 3. Ternary phase diagram of various ratio of gasoline-diesel-biodiesel blends stored at (**a**) 10–20 °C for 1 h and (**b**) 25 °C for 45 days (Adapted from [106]).

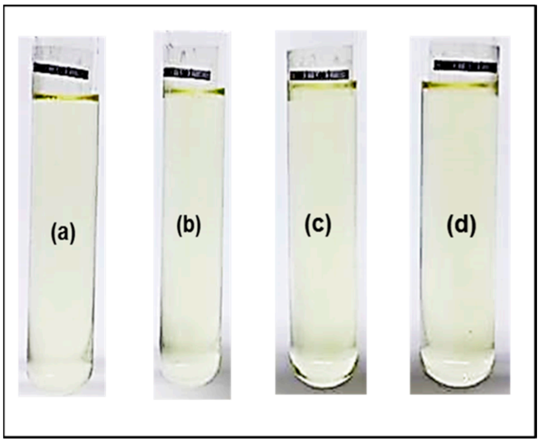


Figure 4. The appearance of gasoline-biodiesel blended fuels (GB) with biodiesel concentrations of (**a**) 20%, (**b**) 15%, (**c**) 10% and (**d**) 5% (Adapted from [106]).

Table 2. Physical properties of the fuels.

Test Item	Unit	Test Method	Gasoline	GB05	GB10	GB15	GB20	B100	Diesel
Heating value	MJ/kg	ASTM D240:2009	45.86	45.32	44.92	44.57	43.6	39.79	45.93
Kinematic Viscosity (40 °C)	Mm^2/s	ISO 3104:2008	0.735	-	-	-	-	4.229	2.798
Lubricity	µm	ISO 12156-1:2012	548	290	282	252	236	189	238
Cloud Point	°C	ISO 3015:2008	−57	−37	−32	−20	−16	3	−5
Pour Point	°C	ASTM D6749:2002	−57	−57	−57	−57	−57	1	−9
Density (15 °C)	kg/m^3	ISO 12185:2003	712.7	722.3	732.2	742.6	757.1	882.3	826.3

5.4.2. Spray Behaviors of Gasoline-Biodiesel Blending Fuel

In LTC and or GCI engine combustion, the main requirement of these concepts is the availability of a homogeneous fuel–air mixture before the start of combustion or prevention of locally fuel-rich mixture regions and the reduction of the in-cylinder combustion temperature. Because GCI uses the direct injection method, therefore the perfection of the spray breakup, evaporation, and mixing processes are most critical in obtaining the optimum combustion and emission performance. The increased surface area of a finely atomized spray enhances fuel evaporation and combustion rate, and the distribution and concentration of fuel vapor directly affect the combustion efficiency and emissions. In other word, the fuel atomization characteristics are very important parameters in a GCI engine because an increase in the number of small droplets means an increase of droplet surface area from the same volume of injected fuel spray, and optimum of the heat and energy transfer can be efficiently achieved through the droplet surface. Thus, how to control and obtain the efficiency of the atomization characteristics and process are very relevant to LTC and GCI concepts. Especially in GCI, due to the direct injection, controlling and managing spray characteristics to obtain efficient atomization is very relevant.

The spray behaviors of the non-vaporizing transient of gasoline and biodiesel blended into gasoline for 10%, 20% and 40% by volume under low-load conditions and various injection pressures were studied by using a constant volume chamber (CVC) [107]. The experimental CVC system can be seen in Figure 6 and a detailed explanation about the system can be found in the previous studies by Kanti et al. [107], and Thongchai and Lim [106]. The main finding is that 100% gasoline indicates significant atomization characteristics and increased gasoline fraction in gasoline-biodiesel blends lead to better quality of fuel and air mixes because of the atomization behaviors as indicated by the low Ohnesorge and high Reynolds number. The Ohnesorge diagram for the fuels in 1000 g/m^3 and 20,000 g/m^3 ambient gas density in 400, 800 and 1200 bar common-rail pressure can be seen in Figure 7.

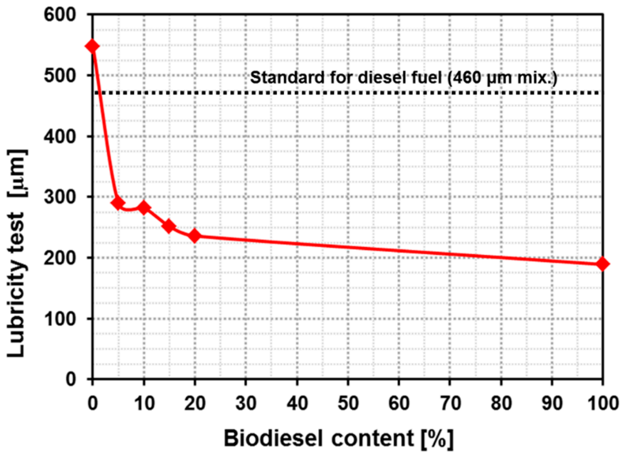
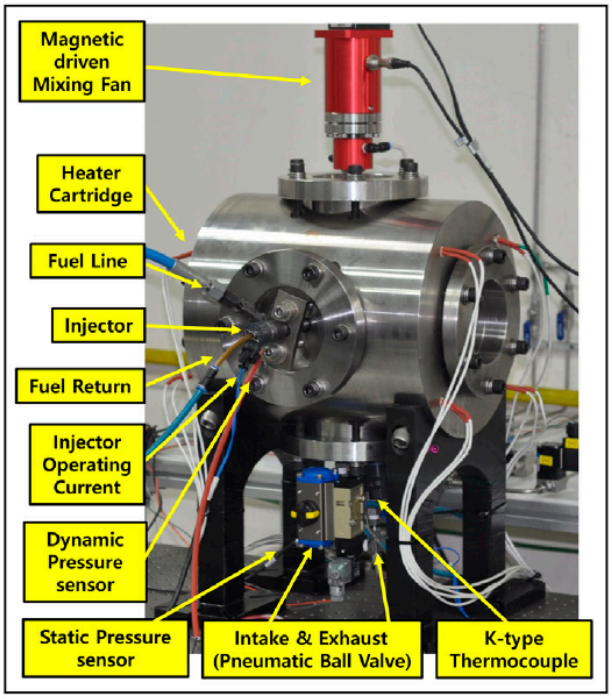


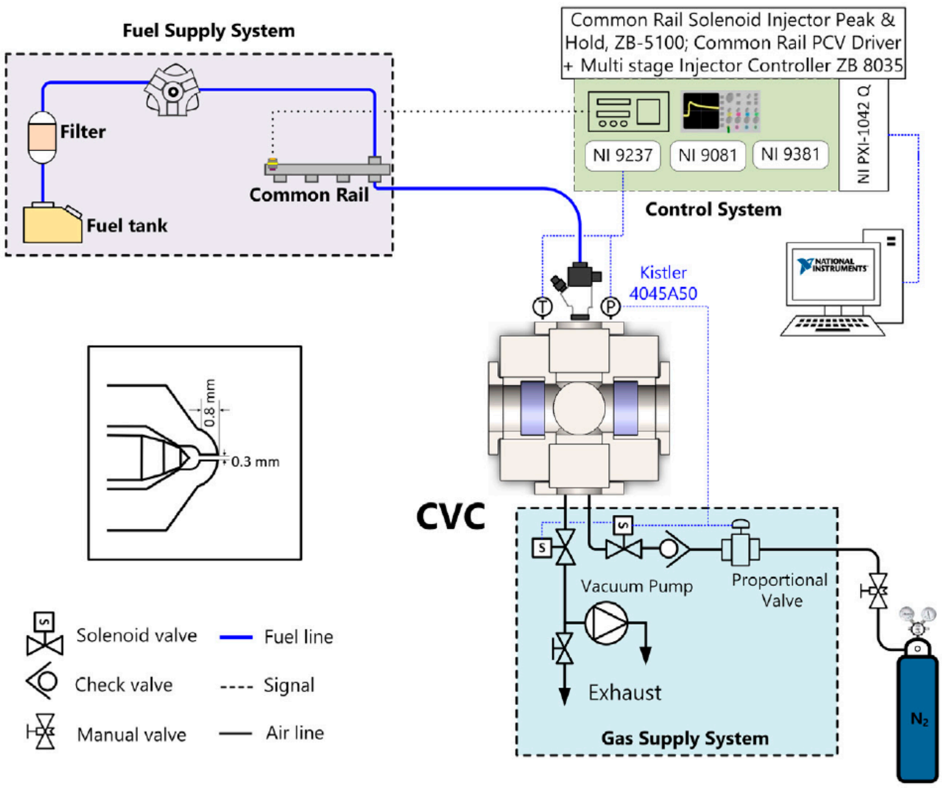
Figure 5. Effect of biodiesel concentration on gasoline- biodiesel lubricity.

The pressure of injection and period are also key combustion and behaviors of emission of GCI engines. The influence of the pressure of injection variations and period of injection on the fuel quantity when using different gasoline-biodiesel blends were investigated and compared [108]. The increase of injection pressure produces a bigger injection quantity for the fuels tested as seen in Figure 8 [108]. At each injection pressure, pure diesel (D100) results in a little bit smaller injection quantity than the gasoline-biodiesel blends. This condition indicates that a longer injection period is needed to deliver the same quantity of fuel when using conventional diesel fuel relative to the gasoline blends. Furthermore, when the quantity of biodiesel blended with gasoline is higher, the injection quantity is decreased (D100 < GB20 < GB10 < GB05). However, a longer injection period has no effect on the injection quantity for various fuels because a long injection duration enables to the work in a quasi-steady state flow duration in which the various densities or viscosities do not influence the amount of injected fuel [77].



(**a**)

Figure 6. *Cont.*



(**b**)

Figure 6. Experimental systems. (**a**) Pictorial representation of constant volume chamber (CVC), (**b**) Schematic diagram of the experimental system [Reprinted from Fuel Processing Technology, Vol. 178, Shubhra Kanti Das, Kihyun Kim, Ocktaeck Lim, Experimental study on non-vaporizing spray characteristics of biodiesel-blended gasoline fuel in a constant volume chamber, Copyrights (2018); with permission from Elsevier].

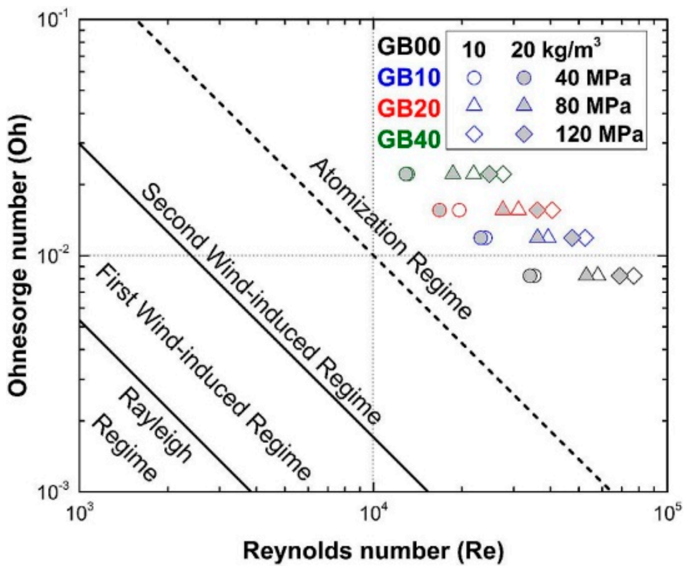


Figure 7. Ohnesorge diagram for all fuels under 10 kg/m^3 and 20 kg/m^3 ambient gas densities under 40, 80 and 120 MPa rail pressures [Reprinted from Fuel Processing Technology, Vol. 178, Shubhra Kanti Das, Kihyun Kim, Ocktaeck Lim, Experimental study on non-vaporizing spray characteristics of biodiesel-blended gasoline fuel in a constant volume chamber, Copyright (2018); with permission from Elsevier].

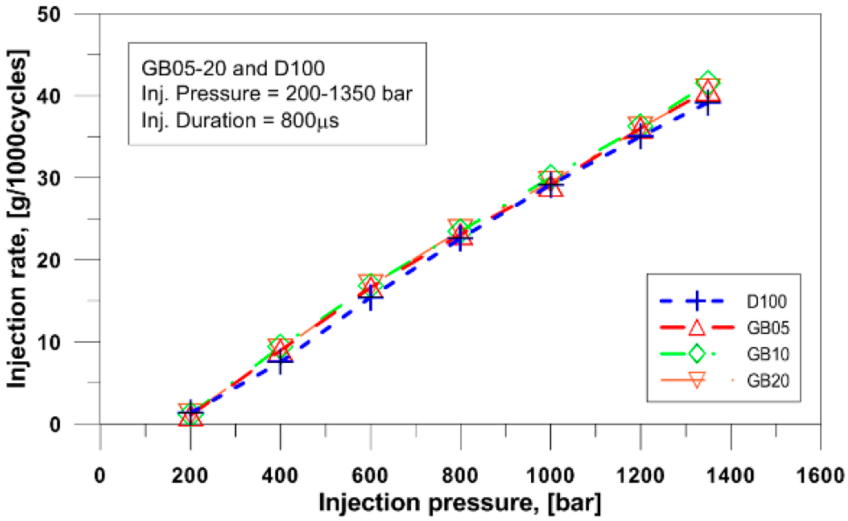


Figure 8. The effect of injection pressure on injection flow rate of a gasoline-biodiesel blend [Reprinted by permission from (the RightsLink Permissions Springer Nature Customer Service Centre GmbH): (Springer Nature) (Journal of Mechanical Science and Technology) [108], Copyright (2018)].

5.4.3. Auto Burning Behaviors of a Blended of Gasoline-Biodiesel

The biodiesel content effects of on the ignitability for gasoline–biodiesel blends were investigated using a rapid compression expansion machine (RCEM) [109]. The main finding was that a low fraction of biodiesel can enhance the autoignition behavior of gasoline as can be observed in Figure 9 [109]. The gasoline-biodiesel mixed fuel with bigger biodiesel content indicated a faster CA10 and no combustion at a lower temperature injection. Misfiring was detected at ambient temperatures at injection timings lower than 522 °C, 512 °C, 492 °C, 477 °C, and 559 °C for GB5%, GB10%, GB15%, GB20%, and G100%, respectively. A gasoline-biodiesel blended fuel with a bigger biodiesel ratio exhibited a smaller temperature of no combustion condition. This is the reason that biodiesel has a higher cetane number than gasoline and biodiesel.

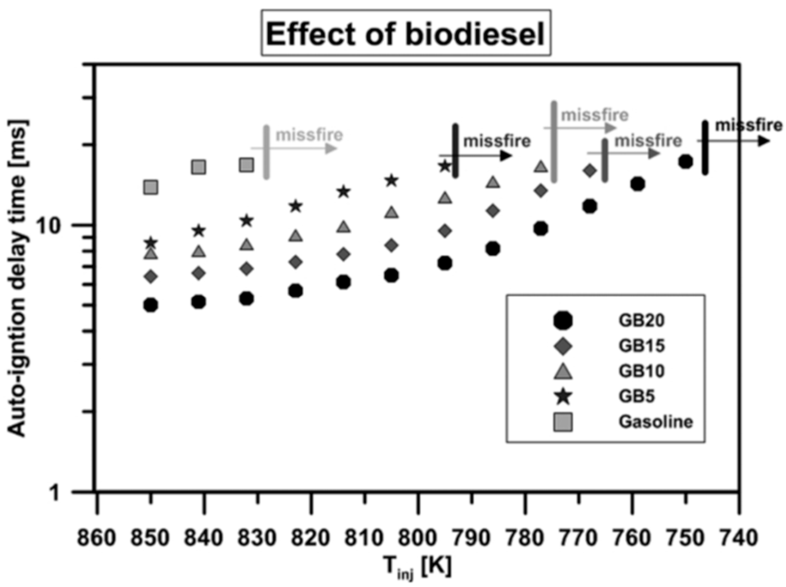


Figure 9. Effect of the biodiesel fraction on auto-ignition [Reproduced with permission from Vu, D.N.; Das, S.K.; Jwa, K.; Lim, O., Proc. Inst. Mech. Eng. Part D J. Authomob. Eng.; published by SAGE publication, 2018.].

5.4.4. Single Injection Mode of Gasoline-Biodiesel Blend

An experimental study on the engine combustion process and exhaust emission characteristics in an effort to simultaneously increase the efficiency of engines and reduce the exhaust emissions such as HC and CO, using a single injection strategy of GCI fueled with gasoline-biodiesel blends was conducted previously [105]. For every variation of start of injection of biodiesel blend in gasoline of the GCI engine, the IMEP was similar to 100% diesel. In addition, the combustion quality, which is represented by the variability coefficient of IMEP (COV-IMEP), indicated that all differences in start of injection of the biodiesel-gasoline blends reflected greater confidence compared to neat diesel. Lastly, the peak of combustion efficiency and smallest THC emission were achieved for GB20 with 40 °CA BTDC of injection timing, as can be observed in Figures 10 and 11.

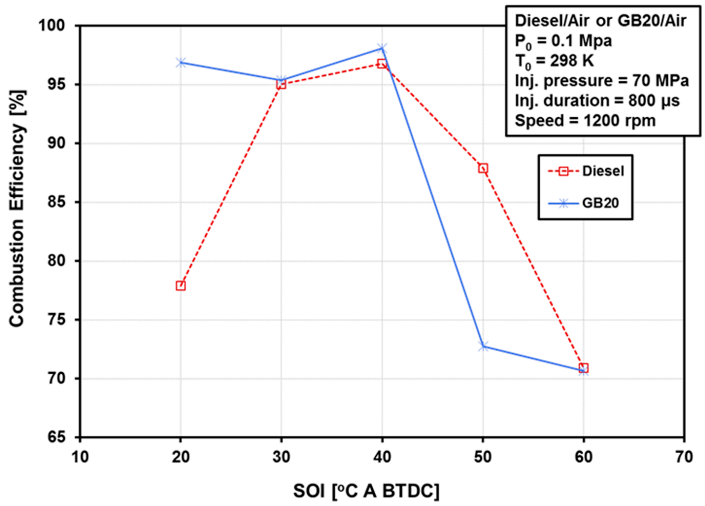


Figure 10. Combustion efficiency [Reprinted from Fuel, Vol. 189, Yanuandri Putrasari, Ocktaeck Lim, A study on combustion and emission of GCI engines fueled with gasoline-biodiesel blends, Copyright (2017); with permission from Elsevier].

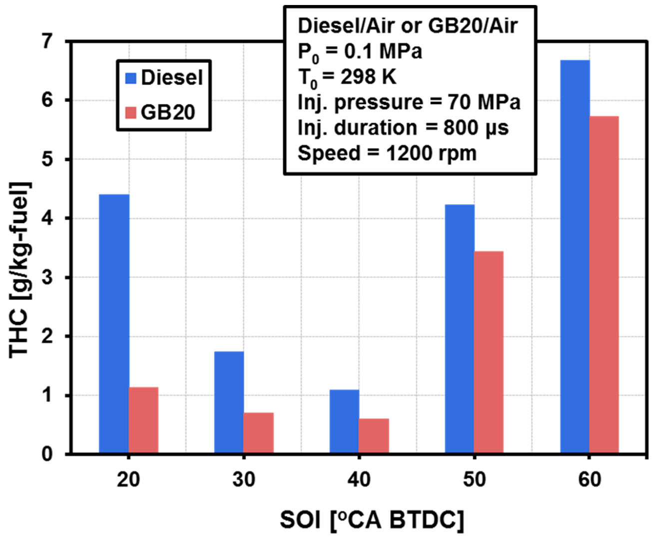


Figure 11. THC emissions [Reprinted from Fuel, Vol. 189, Yanuandri Putrasari, Ocktaeck Lim, A study on combustion and emission of GCI engines fueled with gasoline-biodiesel blends, Copyright (2017); with permission from Elsevier].

5.4.5. Double Injection Mode of Gasoline-Biodiesel Blends

GCI, where gasoline is used as a fuel in a CI engine without the use of a spark plug, combines the high efficiency associated with a CI engine with the low soot emissions associated with gasoline fuel. Further, combustion is a result of sequential auto burning without propagating flames, resulting in low temperature combustion which in turn significantly reduces NOx. The injection timing (the point in time when the fuel is injected into the engine chamber) is a main parameter determining the ignitability of the gasoline-air mixture, and thus engine operation stability. Double injection by early pilot injection and near top dead center of main injection in combination with high EGR rate is a potential way to extend the ignition delay, by causing the formation of a homogeneous mixture. As known the main concept of LTC combustion is formation of a homogeneous mixture which can be achieved by providing a sufficient premixing period. Lengthening the ignition timing is the most suitable method to obtain a homogeneous mixture because it enables sufficient time for mixing. Furthermore, extension of the ignition timing is possible by reducing the cetane number by adding a fuel with low-cetane and a high-octane number fuel such as gasoline and the relevant method is the GCI concept. Therefore, the proper combination of gasoline fuel, double injection strategy, and EGR in GCI engines can simultaneously reduce NOx and smoke emissions by enabling a sufficient air–fuel mixing period and the formation of a more homogeneous mixture.

A study on one- and many-injection strategies of GCI engine was successfully done to compare 100% gasoline with 5% added biodiesel with 100% diesel fuel to obtain the improvement of efficiency and decreased emission characteristics [110]. The findings were as follows: raising the inlet temperature of air, engine-oil, and engine-coolant and use of a multiple injections method could lead to enhancements of the combustion and thermal efficiencies of the GCI engine. Meanwhile, the quality of combustion study using coefficient of variation of indicated mean effective pressure and cyclic variations of maximum pressure of cylinder indicated a satisfactory result. However, the analysis of cycle to cycle variation for the ignition delay showed that these factors suffered with GB05 in many injection strategies (Figure 12). The earlier pilot injection of 5% biodiesel in gasoline fuel could be an argument for lowering carbon monoxide emissions. The biodiesel fraction and gasoline (as the very vapor fuel in the GB05) exhibited meaningful effects of reducing the emissions of carbon monoxide and total hydrocarbons. The emissions of nitrogen oxide from GB05 blend for either multiple or single injections seem to be higher than that of neat diesel fuel with many injections and even bigger than pure diesel fuel with a single injection method. It is believed to be because of the oxygen fraction in the gasoline-biodiesel blend fuel.

5.4.6. EGR and Intake Boosting of Gasoline-Biodiesel Blend

A study on a GCI engine was conducted by adding 5% biodiesel into gasoline and comparing the results with those from neat diesel in single-injection (PPCI) and multiple-injection (MPCI) modes combined with the application of EGR and intake boosting with the goal of obtaining high efficiency and low emissions.

The most important finding was that using 0.12 MPa of intake boosting reduced the NOx emissions with the gasoline-biodiesel blend by almost half compared to using 0.1 MPa intake boosting. Then, increasing the intake boost significantly reduced the smoke emissions with pure diesel fuel, but increasing the intake boost from ambient pressure to 0.12 MPa increased the smoke emissions for the gasoline-biodiesel blend. A summary of these finding can be seen in Figures 13 and 14.

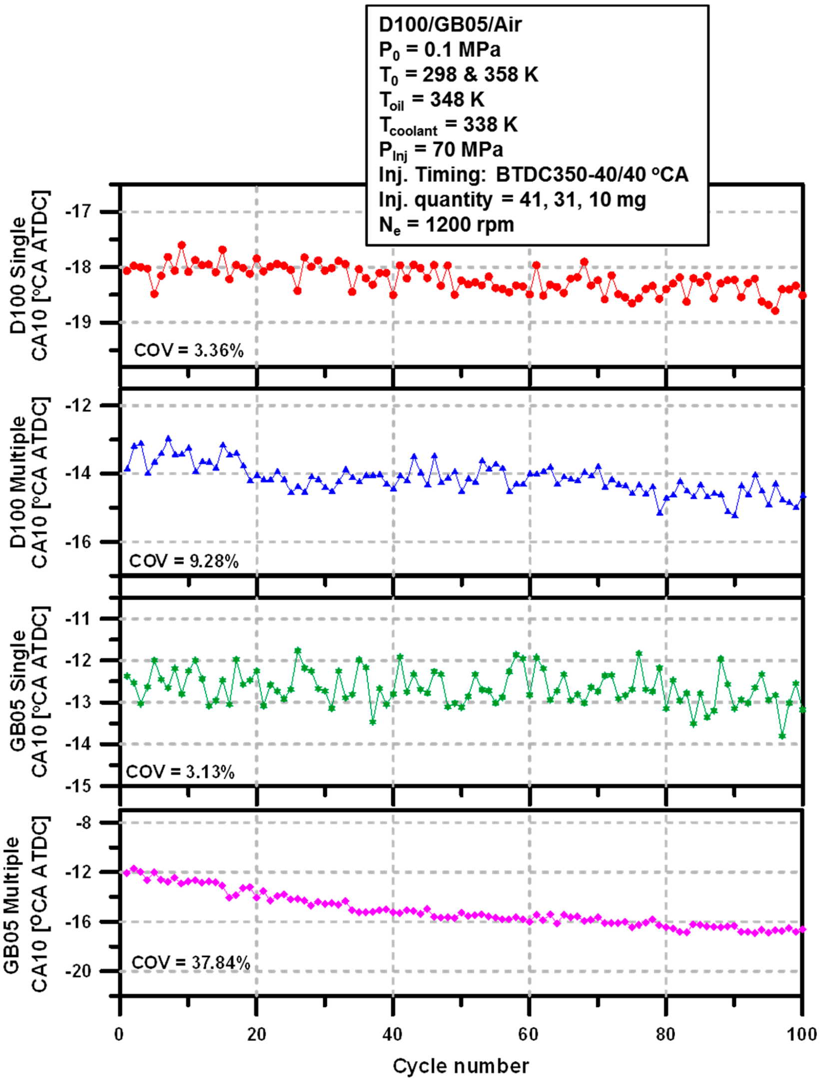


Figure 12. Cycle-by-cycle variations in CA10 under different conditions [Reprinted from Fuel, Vol. 221, Yanuandri Putrasari, Ocktaeck Lim, A study on combustion and emission of GCI engines fueled with gasoline-biodiesel blends, Copyright (2017); with permission from Elsevier.]

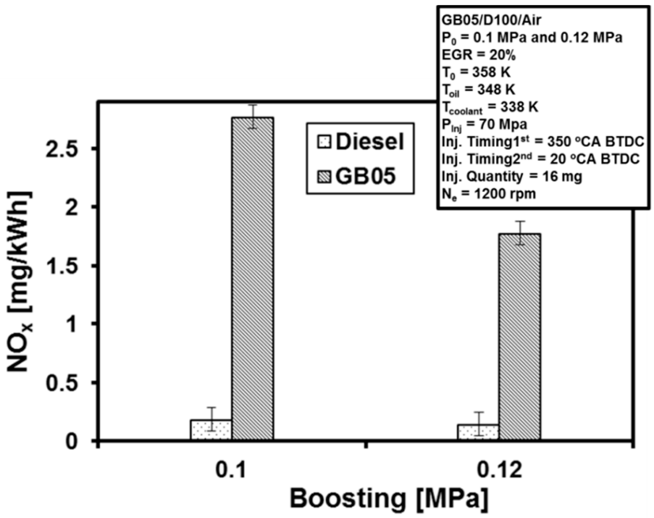


Figure 13. Effect of intake boosting on NOx emissions in MPCI mode.

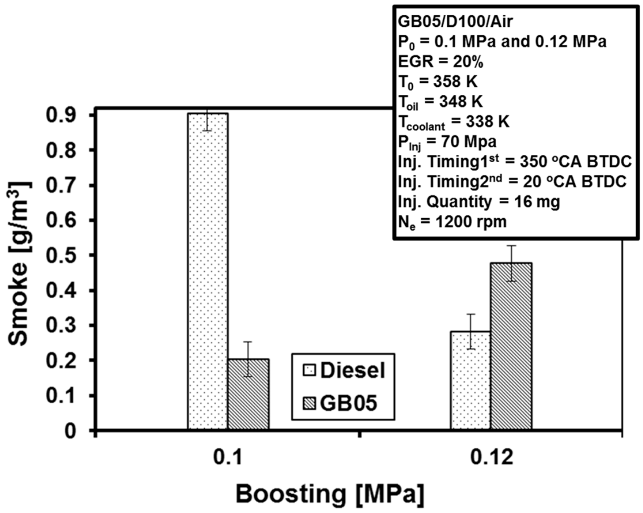


Figure 14. Effect of intake boosting on smoke emissions in MPCI mode.

6. Conclusions and Recommendations

6.1. Conclusions

This study has provided a review of studies on GCI engines fueled with biodiesel-gasoline blends in order to increase engine performance and decrease exhaust emissions. Based on a comprehensive review of the open literature, the present understanding of GCI engines fueled with biodiesel-gasoline blends research work includes the following contributions:

- A literature study of GCI engines potentially fueled with biodiesel-gasoline blends.
- The study on the combustion process and exhaust emission behaviors of gasoline CI engines using various injection timings in a single injection mode fueled with biodiesel-gasoline blends.
- The study about the effects of 5 and 20% biodiesel-gasoline blends on the efficiency and exhaust emissions in gasoline compression ignition engines under single injection mode.
- A study of the combustion and exhaust emissions of a gasoline CI engine fueled with biodiesel-gasoline through a double injection method which comprises of pilot and main injection.
- Experimental investigation of the combustion process and emission behaviors of CI engines fueled with biodiesel-gasoline blends in the early injection HCCI mode.
- An investigation on the effect of EGR and inlet boosting on the process of combustion and emission behaviors of a GCI engine using gasoline-biodiesel-blends.

6.2. Recommendations

Some valuable insights and new ideas were identified based on an experimental series and extensive investigation into GCI engines fueled with a mixture of gasoline and biodiesel. These have not been pursued more fully further within the current research. The following suggestions are provided for future research:

- Use of hot EGR to raise the inlet temperature and a smaller fuel injection pressure (to minimize too much mixing and cylinder wall-wet/impingement of fuel) is required for the GCI engine concept of volatile/vaporizable/less-reactivity and also low cetane-number fuels at smaller engine speeds or engine operating loads.
- Several issues related to the emission and combustion behaviors of gasoline CI engines using blends of biodiesel in gasoline need to be studied further, including stability under low and middle load conditions, cold start and idle conditions, operation in acceptable transient conditions, noise/engine sound quality and in-cylinder PRR at middle and big loads through injection of

fuel methods, exhaust emissions (especially HC, carbon monoxide, NOx and smoke emissions control), LTO and diesel particulate filters (DPFs).

- Several issues related to hardware optimization of gasoline CI engines using a mixing of gasoline-biodiesel also need to be studied further. In this case they include: the combustion chamber/cylinder-head/piston-crown design, injectors holes and angles, injection arrangement and injection method systems, cooled and uncooled EGR, turbochargers combined with superchargers or boosting to obtain higher intake pressures at big EGR ratio, subsequent/exhaust treatment, and quality of fuel (lubrication behavior, viscosity, and detergent-like properties). Thus, advanced additive technology has to be implemented for the various conditions come upon in gasoline compression ignition engines.
- More significant experimental, simulation and development studies and work are required to push gasoline compression ignition engine technology to the step of real application.

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