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REVIEW ARTICLE

Strategies to Form Homogeneous Mixture and Methods to Control Auto-Ignition of HCCI Engine

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ABSTRACT – Homogeneous charge compression ignition (HCCI) engine has emerged as a promising combustion technology. Theoretically, an HCCI engine can reduce both NOx and soot emissions significantly down to almost zero levels. This is possible as a result of two fundamental processes that occur in the HCCI engine, i.e. the homogeneous mixture and its autoignition characteristics. Neither spark plug nor injector is used in the HCCI engine. The autoignition of the homogeneous mixture is solely influenced by its chemical reactions inside the combustion chamber. However, this is where the problems start to occur. At low loads or too lean mixtures, misfire may occur, thus increasing the HC and CO emissions. At high loads or too rich mixtures, soot emissions and knocking tendency may increase. Moreover, an undesirable pressure rise due to knocking will increase the combustion temperature and potentially increase the probability of NOx formation. Therefore, the operating range of HCCI engine is very limited only to part loads. Controlling its combustion phasing play an important role to extend the narrow operating range of the HCCI engine. Despite numerous review articles have been published, classification of the approaches to achieve HCCI combustion in diesel engines were rarely presented clearly. Therefore, this review article aims to provide a concise and comprehensive classification of HCCI combustion so that the role and position of each strategy found in the literature could be understood distinctively. In short, two important questions must be solved to have successful HCCI combustion; (1) how to form a homogeneous mixture? and (2) how to control its auto-ignition?

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NOMENCLATURE

SI	Spark Ignition	MULDIC	MULtiple stage Diesel Combustion
DPF	Diesel Particle Filters	NTC	Negative Temperature Coefficient
SCR	Selective Catalytic Reduction	PCI	Premixed Compression Ignition
DOC	Diesel Oxidation Catalyst	UNIBUS	UNIform Bulky combustion System
HCCI	Homogeneous Charge Compression Ignition	DPNR	DeNOx and Particulate Number Reduction
PPCI	Partially Premixed Compression Ignition	IFP	Institut Français de Pétrole
RCCI	Reaction Controlled Compression Ignition	MK	Modulated Kinetics
CAI	Controlled Auto-Ignition	HPLI	Highly Premixed Late Injection
PFI	Port Fuel Injection	HCLI	Homogeneous Charge Late Injection
COV of IMEP	Coefficients of Variation in Indicated Mean Effective Pressure	TSDI	Two-stage direct injection
COV of P_{max}	Coefficients of Variation in Peak Cylinder Pressure	HiMICS	Homogeneous charge Intelligent Multiple Injection Combustion System
CA50	Crank Angle of 50%	VCR	Variable Compression Ratio
DI	Direct Injection	VVT	Variable Valve Timing
PREDIC	PREmixed lean DIesel Combustion	EGR	Exhaust Gas Recirculation

INTRODUCTION

As emission regulation is increasingly stricter throughout the world, research and development towards cleaner and more efficient engines are extensively conducted [1-4]. Gasoline or spark ignition engine is famous for its less emission and noise but has low thermal efficiency [5-8]. Diesel or CI engine, on the other hand, has relatively higher thermal efficiency, durability, and low-cost characteristics but produces more harmful pollutants and noise than a gasoline engine [9-13].

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The diesel engine is currently considered as one of the lowest well-to-wheel CO_2 system owing to the development of high-pressure common-rail direct injection [14, 15]. However, it suffers from the trade of NOx and PM emissions [16-22]. The emissions are detrimental not only to the human being but also to the environment [23-25]. Authorities around the world then propose regulations to limit engine-out emissions. To meet such increasingly stringent emission regulations, the automotive industry is forced to reduce harmful engine emissions [26-28]. Numerous after-treatment technologies have been proposed, including Diesel Particle Filters (DPF) [29-38], Selective Catalytic Reduction (SCR) [39-46] and Diesel Oxidation Catalyst (DOC) [47-52]. These methods have been successfully applied to reduce harmful emissions in diesel engines. Despite being very effective to reduce emissions of diesel engines, the use of exhaust after-treatment devices will add the production cost of a vehicle, making it uneconomically feasible [53].

Homogeneous charge compression ignition combustion emerges as a promising technology not only to reduce harmful emissions but also to improve engine efficiency [54-56]. The HCCI engine offers both potential economic and environmental advantages [57, 58]. This combustion concept combines the competitive advantage from gasoline and diesel engine. It allows an engine to operate with high thermal efficiency as a diesel engine but with low emissions as a gasoline engine. Figure 1 shows the positioning of the HCCI engine among the existing technology of internal combustion engines. The HCCI belongs to CI engine as its combustion is triggered by the compression of a piston moving upwards towards TDC instead of by the spark plug as in SI engine.

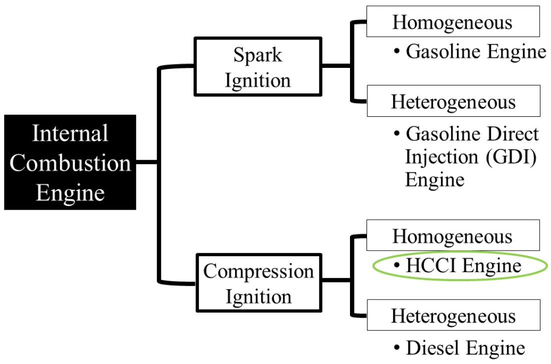

Figure 1. The positioning of HCCI engine compared to conventional engines.

Several reviews addressing HCCI combustion have been published and can be found in the literature [59-63]. However, a review article that provides a clear classification of several strategies implemented in the HCCI engine is difficult to find. It is the objective of this review article to provide concise and comprehensive strategies for HCCI combustion in a diesel engine. This review divides its content into two major categories; (1) strategies to form a homogeneous mixture and (2) methods to control HCCI auto-ignition. Prior to these main themes, the fundamentals of HCCI combustion are firstly explained. Problems and challenges of this advanced combustion system are also discussed. The schematic classification to achieve HCCI combustion in diesel engines is proposed, as shown in Figure 2. It shows the classification of how to achieve homogeneous mixture and methods to control HCCI combustion phasing. This review includes results from published papers after 2015. However, when pioneering studies could help facilitate the understanding of important concepts and approaches, the ground-breaking results were traced back to their original sources, thus some old studies are found in the references.

POTENTIAL AND CHALLENGES OF HCCI ENGINE

Numerous names for the low-temperature combustion concepts have been proposed by a number of research groups such as Partially Premixed Compression Ignition (PPCI) [64-68] and Reaction Controlled Compression Ignition (RCCI) [69-75]. Despite its variety, the names imply two basic principles: the premixed homogeneous air/fuel mixture and the autoignition of its combustion. The term of HCCI was firstly proposed by Thring [76] and is sometimes used both in gasoline and diesel engines. However, it is important to note that in some articles and books, the term of Controlled Auto-Ignition (CAI) is often used for gasoline engines. The reason why CAI is more suitable to be used in gasoline engines is that the autoignition of gasoline engines is not triggered by the compression-ignition like the diesel engines. Rather, the autoignition is initiated by the intake charge heating or convective heat transfer from the hot burned gases. Furthermore, the homogeneous charge is an idealistic terminology, charge stratification is often observed especially between the trapped burned gases and the air/fuel mixture. In fact, charge stratification is occasionally used to change the autoignition and control the heat release rate in HCCI engines [77, 78]. In other words, compression is not the only means to achieve the autoignition and obtain the premixed air/fuel mixture. Other factors also play a significant role, such as externally or internally heating. Therefore, the CAI is often preferred for gasoline engines, while the term HCCI is used for diesel engines.

An HCCI engine has no direct mechanism to control its start of combustion. Without the assistance of external devices such as spark plug in SI engines or injector as in CI engines to control its combustion phasing, an HCCI engine relies heavily on the simultaneous reactivity of the entire intake charges in the cylinder. To ensure the auto-ignition and heat release reactions, the temperatures must be sufficient for autoignition. The absence of spark plugs and injector resulted in difficulty to control its combustion phasing, but it has the potential to reduce NOx and soot emissions simultaneously.

Figure 3 shows the advantages of the HCCI engine compared to SI and CI engines. The combustion of the HCCI engine occurs homogenously at multiple locations in a low-temperature environment without the hot flame being produced, thus reducing NOx emissions significantly. Moreover, the fully premixed homogenous mixture has also enabled the soot formation to be avoided. Therefore, HCCI combustion can reduce both NOx and soot emissions simultaneously. This is because HCCI combustion lies outside the soot formation region as the mixture inside the chamber is homogeneously lean (low equivalence ratio). Its temperature range is also low (between 1000 and 1800 K), thus avoiding the NOx formation. However, the HCCI combustion may potentially produce soot and NOx if the equivalence ratio is above 2 (rich mixture) and the local temperature reaches beyond 2200 K, resulted from changes in the composition of intake air and operating conditions.

Despite its promising application, the HCCI engine has still several challenges to solve to be widely used as a commercial machine. These include a limited load capability as well as a problem in controlling its combustion phasing and heat release rate [79]. As the mixture between air and fuel ignites nearly simultaneously, knocking and misfire phenomena are difficult to control, limiting the operating range of HCCI engine.

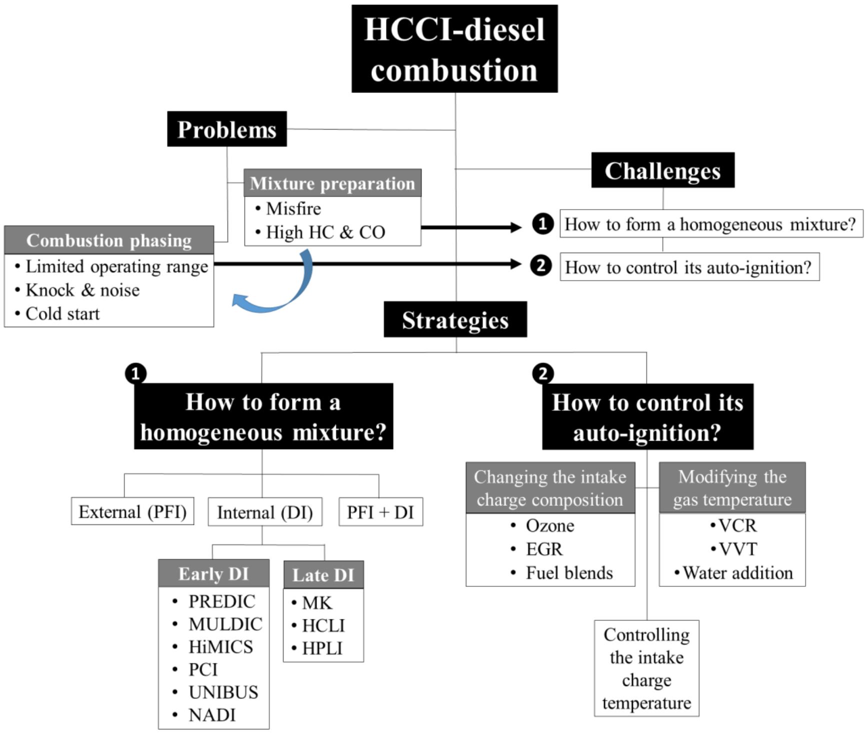

Figure 2. Proposed classification to achieve HCCI combustion in diesel engines.

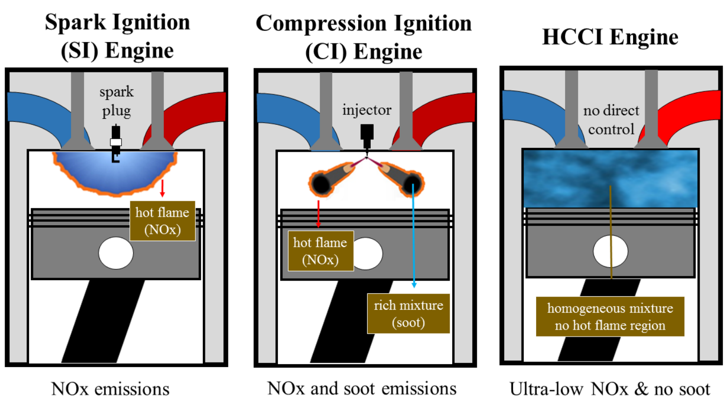

Figure 3. The benefits of HCCI engine compared to SI and CI engines.

In theory, since the combustion occurs simultaneously at lean mixtures throughout the combustion chamber, pressure differences are not observed; thus, knocking can be avoided. At high loads, rich mixtures and the risk of soot formations are unavoidable, while knocking is also prone to occur. When the temperature reaches high above 2200 K, NOx may be produced. On the other hand, at low loads or too lean mixtures, incomplete combustion and misfire may occur, thus potentially increasing HC and CO emissions. Figure 4 summarises the opportunities and challenges of HCCI combustion.

In general, HCCI offers a lower emission and higher fuel efficiency by combining the benefits of two conventional engines, i.e. SI and CI engines. However, several challenges still need to be overcome to extend its operating range. Although a significant reduction of NOx and soot emissions can be achieved from a theoretical point of view, the HCCI engine suffers from high HC and CO as well as NOx emissions resulting from the changes in engine operating conditions as mentioned in the previous paragraph. Figure 5 shows the evolution and topology processes of heat release, combustion and emissions formation of an HCCI engine.

Several challenges must be addressed in order to achieve HCCI combustion. This includes high HC and CO emissions as well as the misfire and knock tendency. However, those challenges can be solved provided that its combustion phasing can be controlled effectively. Therefore, the biggest challenge in HCCI combustion remains controlling its combustion timing and subsequent heat release. Two important issues should be answered to successfully control the combustion phasing of an HCCI engine and extend its operating range. The first is how to form a homogeneous mixture and improve its homogeneity, and the second is how to ignite such a mixture.

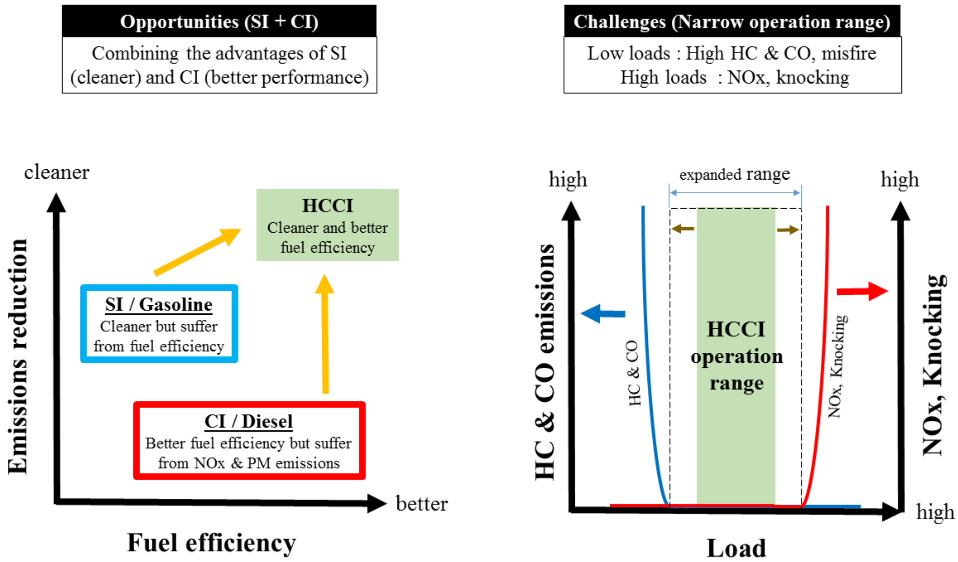

Figure 4. Opportunities and challenges of HCCI combustion.

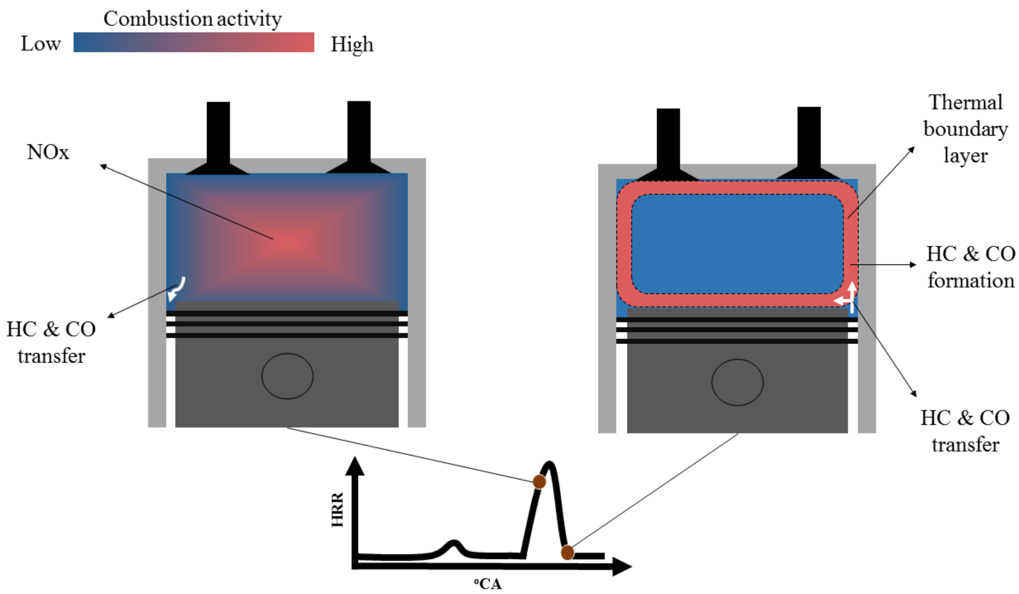

Figure 5. The development of heat release, combustion and emissions formation of an HCCI engine, adapted from [80].

STRATEGIES TO ACHIEVE HOMOGENEOUS MIXTURE

The homogenisation as found in spark-ignition engines is difficult to obtain using diesel fuel in HCCI combustion. Instead of a homogeneous mixture, a stratification occurs in a lean HCCI diesel combustion. Therefore, rich mixtures are present inside the cylinder. However, such non-homogeneous mixtures may be beneficial to prevent extreme heat release, thus reducing the noise, pressure, and knocking initiation. Figure 6 summarises the methods to achieve a homogeneous mixture in HCCI diesel engines.

To form a homogeneous mixture with diesel fuel, a significant amount of time is required. The use of high-pressure injection systems is therefore not a feasible option. To solve this problem, the fuel should be injected in which the mixture has an adequate amount of time to form a homogeneous charge, and at the same time, fuel impingement to the wall is minimised. Adopting a well-advanced injection system could be the solution, either using early direct injection or port fuel injection. However, the early injection could potentially worsen the atomisation and evaporation processes since the fuel is injected in an environment where the density and temperature are still relatively low. Therefore, the addition of a pre-heater to increase the temperature of the mixture is required. In other words, to implement either early direct injection or port fuel injection to ensure the homogeneous mixture, the preheating process is needed. This is because the low air temperature cannot achieve significant evaporation. Vaporisation is crucial here as diesel fuel has low volatility characteristics.

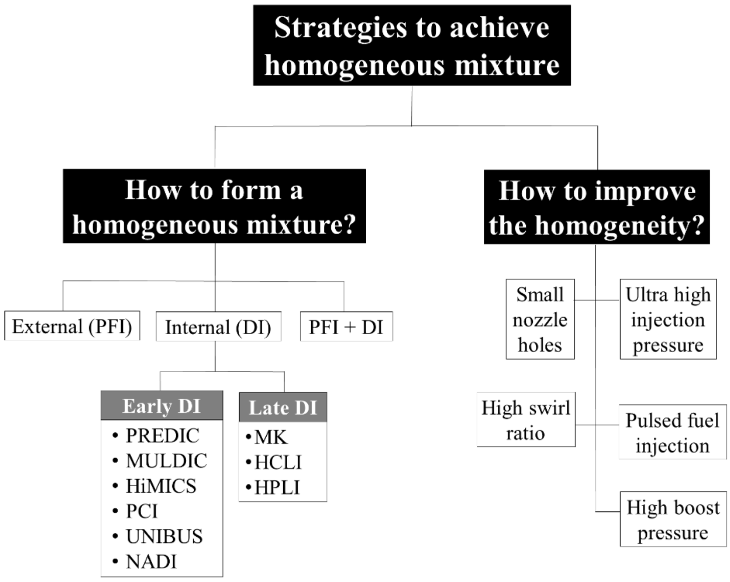

Figure 6. Methods to achieve homogeneous mixture in HCCI diesel engines.

Provided that the homogeneous and lean mixture has been obtained, long auto-ignition delays are achieved due to chemical phenomena instead of physical ones as in spark or compression ignition engines. In the HCCI engine, the combustion is triggered by the high temperature obtained near the TDC. Therefore, the use of diesel fuel, which is known for its high cetane number and two-stage combustion characteristic, could cause too early autoignition.

While the HCCI gasoline engine can improve the efficiency and reduce the NOx emission to near-zero level, the HCCI diesel engine is more towards reducing both the NOx and soot emissions simultaneously by maintaining the engine performance compared to conventional diesel engines. This can be achieved using three approaches, depending on the mixture preparation process; (1) PFI, (2) early and (3) late direct injection. Figure 7 illustrates those three approaches.

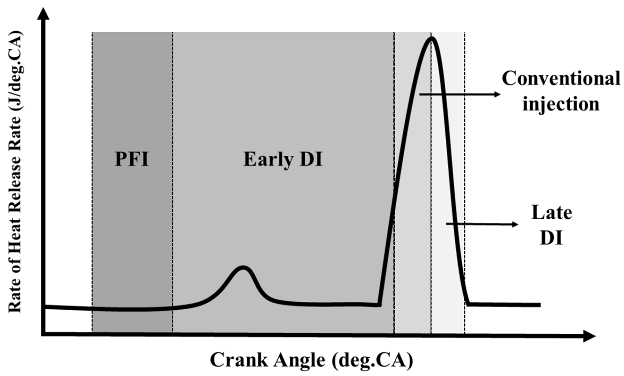

Figure 7. Approaches in HCCI diesel engines, adapted from [81].

External Mixture Preparation Using Port Fuel Injection Strategy

Since homogenisation requires some time, the adoption of a port fuel injection strategy is the preferred method compared to direct injection to form a homogeneous mixture. The homogenous mixture is achieved during intake and compression. The port fuel injection (PFI) of HCCI diesel works similar to conventional gasoline except that the autoignition occurs due to compression instead of the spark plug. Since the fuel is injected long before the intake valve opens, the rate of PFI homogenisation is higher compared to early or late DI injection. As a result, a significant reduction of NOx and soot emissions can be achieved, depending on the local temperature for NOx as well as the degree of evaporation and homogenisation for PM. However, the HC and CO emissions are relatively higher than those of diesel combustion. Both emissions are also affected by the degree of homogenisation.

Fuel evaporation is the major concern in PFI HCCI diesel combustion. It is known that diesel fuel evaporates at a high temperature. However, the normal temperature of the intake manifold is much lower than that is required to evaporate the diesel fuel. That is why the preheating device is required to increase the intake charge temperature so that the fuel evaporation is improved. Otherwise, poor evaporation in the intake manifold will lead to late evaporation in the compression stroke even after the combustion has started. Consequently, the homogeneous mixture cannot be achieved. The fuel will also impinge or condense on the cylinder wall, resulting in high HC, CO emissions and oil dilution [82]. Since part of the fuel does not burn, the combustion efficiency will also suffer.

Heating the intake charge to improve the diesel fuel evaporation may cause a significant problem. The higher temperature of the intake charge resulting from the preheating process will advance the start of combustion. This is because once the diesel fuel evaporates satisfactorily and becomes homogeneous at the intake port, this mixture will flow into the combustion chamber, and its temperature will increase further due to the compression stroke. Therefore, the compression ratios need to be lowered as the ignition temperature will be reached well-advanced before the TDC, affecting efficiency and creating noise.

HCCI combustion stability needs more investigating with the addition of a port fuel injection system. Additional hardware and software need to be installed to control and change critical engine parameters such as intake air temperature. It is generally known that knocking occurs due to overly advanced combustion phasing. On the other hand, at overly retarded combustion phasing, incomplete combustion occurs with excessive HC and CO emissions. To quantify the combustion stability, the coefficients of variation in indicated mean effective pressure (COV of IMEP) and peak cylinder pressure (COV of P_{max}) should also be determined. The combustion phasing is normally defined as the crank angle position where 50% of the energy was released (CA50). It is expected that the cycle-to-cycle variations of the HCCI engine will depend on the combustion phasing. At overly retarded combustion phasing, combustion instability may increase significantly. In general, to achieve a homogeneous mixture, a port fuel injection is normally installed several centimetres upstream of the intake valve in the intake manifold, with the injection timing being set prior to the intake TDC. Sometimes, heating the intake air before it mixes with the fuel injected through the port fuel system is required to help vaporise the mixture.

Internal Mixture Preparation Using Direct Injection (DI) Strategy

A common rail technology has made it possible to control high-pressure fuel injection. As a result, the fuel can be programmed electronically to be injected flexibly. The fuel can be injected either before or after the TDC to achieve a homogenous mixture.

Early DI

An early direct injection system can provide a homogeneous mixture required in HCCI diesel combustion. The well-advanced injection before TDC in the compression stroke can promote fully premixed combustion by allowing enough time between the injection and the ignition. This is the most favourable method in diesel engines to obtain HCCI. This combustion concept is also known as the Premixed Charge Compression Ignition (PCCI) combustion. Unlike PFI HCCI diesel, an early injection system could eliminate the requirement for preheating device to increase the intake air charge. This is because the gas temperature and density at which the fuel is injected are sufficiently high to improve the evaporation of the diesel fuel. As a result, the preheating device may not be needed, and the time to prepare the homogeneous mixture is also relatively less. With no preheating process, the intake charge temperature of early injection is lower compared to that of PFI. As a result, the problem with early autoignition is also fewer. In addition to the absence of a preheating device, an early injection system also allows the same fuel injection to be used for both HCCI and diesel combustion, thus extending its operating range. The combustion is relatively easier to control, and the transition from a low load of HCCI to a high load of the conventional diesel engine would also be smooth.

However, controlling the combustion phasing remains a major issue here as there is no direct control between the start of injection and the start of ignition. Another disadvantage is the wall wetting. When fuel is injected early in the compression stroke, the cylinder environment is still low density. Therefore, fuel impingement and wall wetting are the main concern with early injection. In order to avoid wall wetting so that HC and CO emissions and fuel efficiency can be improved, the modification of the injector system and its geometrical configuration are required.

It is also important to note that the time to prepare the homogeneous mixture in the early injection is also relatively less compared to PFI. Some heterogeneous mixture is therefore unavoidable, resulting in higher NOx and PM emissions than those of PFI but still far lower than conventional diesel combustion. Numerous approaches have also been proposed using early direct injection. They are varied in terms of the numbers of the injector (one or more) and the injection events (single or multiple). Some of the pioneering early injection systems are illustrated in Figure 8. The development of PREmixed lean DIesel Combustion (PREDIC) was initiated by Japanese researchers in New ACE Institute [83]. They used various injector configurations, locations and injection timing and found that low NOx and soot emissions were successfully obtained. The reduction in both emissions was mostly caused by the injection timing, geometrical arrangement and charge dilution. The use of two side injectors, reduced nozzle orifice diameter and more orifices were able to decrease the HC and CO emissions using conventional DI injector. Well-advanced injection achieved a maximum load of 50 bar IMEP [84].

In another study, lower HC emission and higher combustion efficiency were achieved using a swirling-flow pintle-nozzle injector [85]. Such injector was found to help to form a more homogeneous mixture, thus reducing HC emission and increasing combustion efficiency. Akagawa et al. [86] revealed that a naturally aspirated diesel engine was only able to achieve a maximum load of approximately 50% of the IMEP, i.e. the upper limit of PREDIC. Like the PREDIC, the MULtiple stage Diesel Combustion (MULDIC) was also developed in New ACE Institute of Japan to increase the operating range of the PREDIC [87]. It is generally known, the early start of injection is limited by misfiring caused by the over mixing resulting from a too early injection. With the too late injection, knocking may occur. Hashizume et al. [87] developed the MULDIC by introducing a second injection close to TDC. It combines the PREDIC with conventional diesel combustion. As the second stage combustion used conventional diffusion combustion similar to a diesel engine, the NOx and soot emissions are relatively higher than those of the PREDIC. However, the NOx emissions were still significantly lower, while the particulate emissions were higher compared to conventional diesel combustion. Yet, since the fraction of particles contained high soluble organic, a simple oxidation catalyst can be used.

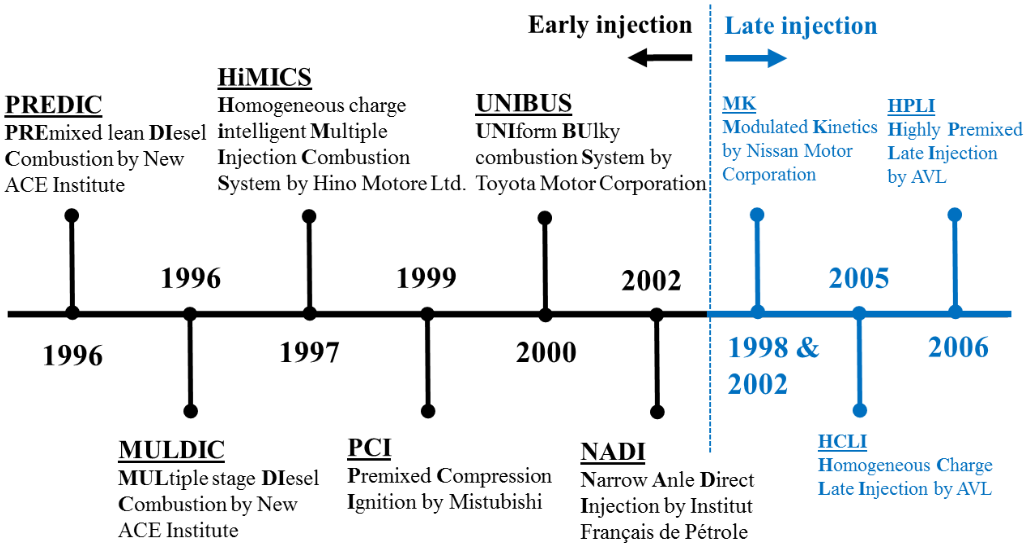

Figure 8. Pioneering studies in DI HCCI diesel engines.

Hino Motors Ltd. [88, 89] developed the Homogeneous charge Intelligent Multiple Injection Combustion System (HiMICS). The HiMICS used a conventional rail system and multiple injections by using a hybrid injection pattern. Like the MULDIC, the HiMICS combined the early injection and the main injection close to TDC. However, a post-injection after TDC was introduced to lower soot emissions. The HiMICS used a conventional 6-orifice nozzle and a 30-orifice 3-row nozzle. The 6-orifice nozzle gave a better injection around TDC, while the 30-orifice nozzle improved the mixture formation. This indicated that the use of a double nozzle injection system was required to achieve both improved injection and homogeneous mixture.

Mitsubishi developed the Premixed Compression Ignition (PCI)[90] by combining a conventional DI diesel injector nozzle, early start of injection and a lower compression ratio. The orifices angle was varied, and it was found 80^o angle gave the best result with a single injection at around 60-40 CAD before TDC. The results gave negligible NOx and tolerable HC emissions, but the soot emission was observed. To solve the soot emissions problem, a nozzle tip with two rows of orifices whose sprays impinge with each other has improved the fuel dispersion and reduced the spray penetration. Therefore, nearly zero soot emissions is achieved.

Although it is acceptable, the HC emissions of the PCI are still relatively high. An oxidation catalyst was used to reduce the HC emissions, similar to a traditional diesel engine without a catalyst. Moreover, cooled EGR was also used to retard the start of combustion thereby increasing the maximum load. With the assistance of a boost pressure of 1.80 bar, comparable performance and fuel consumption to a conventional diesel engine with a significant reduction in NOx and negligible soot emissions were achieved. Furthermore, the maximum load can also be further increased using a split injection. The first injection was used to achieve the combustion of premixed compression ignition, while the second injection resulted in more diesel-like combustion [91]. As a result, NOx and soot emission were significantly reduced and high combustion noise at high load was avoided

Toyota developed the UNIform Bulky combustion System (UNIBUS) particularly for the low load, low-speed region [92-94]. As for the high load and high speed, traditional diesel combustion is used. It was commercialised in 2000 and used as a rich combustion strategy for the Toyota DPNR system (DeNOx and Particulate Number Reduction). The UNIBUS combined pilot and late injection to enhance combustion efficiency without increasing HC and CO emissions.

The pilot injection aims to form a homogeneous mixture, while the late injection is used to burn both the pilot injection and premixed fuel of the late injection.

The Institut Français de Pétrole (IFP) developed the Narrow-Angle Direct Injection (NADI) with a narrow-angle of 80 degrees [95]. The fuel was injected well-advanced in the compression stroke when temperature and density were still low. The narrow angle could avoid wall wetting. The NADI allowed the HCCI-Diesel to be operated at full load with modification to the piston-bowl geometry. The HCCI combustion was operated at low to medium load and was switched to diesel combustion at higher load. The next development of NADI used a common rail system, allowing for split injection at low loads to decrease HC and CO emissions. The split injections improved the soot oxidation due to the vortices creation from the narrow bowl. Ultra-low NOx and soot, as well as tolerable HC and CO emissions, were obtained with high efficiency [96]. However, high EGR rate control was required.

Late DI

In early DI injection of HCCI combustion, the fuel is injected well-advanced in the compression stroke, allowing enough time to achieve the homogeneous mixture. The closer the injection to the TDC, the higher the gas temperature and density, thus shortening the autoignition delay. When the injection is further retarded after the TDC, the gas temperature and density are relatively lower due to the expansion of downward piston movement. As a result of this late injection, longer ignition delay and improved mixture formation are achieved, which are preferred for HCCI combustion. If combined with high EGR rates, a longer ignition delay can be even more achieved, allowing the formation of fully premixed combustion. Consequently, soot formation is inhibited due to the premixed combustion mode and NOx is also avoided due to low combustion temperatures.

In general, the late injection of HCCI engine offers two major advantages. Firstly, it is easy to be implemented in conventional diesel engines. Secondly, the injection and combustion are not separate systems; thereby, the injection timing control indirectly the combustion phasing. However, the challenge in the late injection of HCCI engine remains the maximum load that can be obtained without penalty in efficiency. The modulated kinetics (MK) and highly premixed late injection (HPLI) work on the basis of late injection of HCCI engine.

Nissan Motor Corporation developed the MK [97, 98] and was introduced in the Japanese market in 1998 for high-speed diesel engines. The first generation of MK technology depends on three conditions: the reduction of oxygen concentration, the retardation of ignition start and the improvement of the mixture formation. The reduction of the oxygen concentration of the intake air was achieved using EGR resulted in a significant decrease in NOx emissions, but with a penalty on soot and HC emissions. Moreover, the retardation of ignition led to more premixed combustion with lower soot and NOx, but higher HC emissions were reported. Lastly, the improvement of the mixture formation was achieved using a high swirl ratio resulted in further soot reduction and a significant reduction in HC emission. These three aspects enabled the application of late injection in HCCI engine by increasing the ignition delay [98, 99].

The second generation of the MK system was able to extend the load and speed range of HCCI engine by using the same principle as its first-generation concept. The compression ratio was reduced and EGR cooling was used to increase the autoignition delay. The injection pressure and the nozzle diameter were increased to reduce the injection duration. The reduction of oxygen concentration and the retarded start of injection contribute to the reduction of NOx and soot emissions. Ultra-low soot emissions were achieved regardless of the equivalence ratio if all fuel is injected before the start of combustion [100].

The AVL developed both the homogeneous charge late injection (HCLI) and highly premixed late injection (HPLI).[101] HCLI could be used at low load, while the HPLI was used at medium load and conventional diesel combustion was used at high load. In the HCLI, to ensure rapid homogenisation, the injection is performed at around 40 degrees before TDC similar to the early injection system. The injection does not control the start of combustion and the burn rate, but the reaction kinetics of cylinder charge does. Therefore, the mixtures variables and composition at the end of intake determine the start of combustion. To prevent premature autoignition, the compression ratio was reduced compared to the conventional diesel engine and higher EGR rates of more than 65% was selected. At high combustion speed, pressure rise rates become very high, thus causing combustion noise. As a result, engine efficiency would be affected.

In the HPLI, the fuel is injected late after TDC. The injection is started late to delay the ignition in order to achieve the homogeneous mixture. The mixture homogenisation depends on the interval between the end of injection and the start of combustion. In the case that the injection and combustion phasing overlap, excessive soot emissions are produced. To oxidise these soot emissions, a slightly higher temperature is maintained at the end of combustion. As a result, NOx emissions can also be reduced using EGR rates of 40%.

Combined mixture preparation (PFI + DI) strategy

In addition to external and internal strategies to form a homogeneous mixture, one feasible approach to improve HCCI diesel operating range is by combining the PFI with a DI close to TDC. By combining PFI and DI, the combustion phasing could be controlled. This approach will help to achieve higher loads condition using conventional diesel combustion. To conclude for this section, some important recent studies to achieve a homogeneous mixture for HCCI combustion in the diesel engine are shown in Table 1.

Table 1. Recent studies employing various strategies to achieve a homogeneous mixture for HCCI combustion.

Strategies	Base engine	Injector specification	Major findings	Refs.
Port fuel injection	4-cylinder, 1998 cc, common rail (1600 bar), diesel engine with 18.2:1 compression ratio	A port intake injection was fabricated in-house similar to low-pressure gasoline-type injectors with one port intake injection in each intake runner	PFI provided the versatility of a basic fuel supply and control system while preserving the direct injection of diesel fuel and the initial hardware specification.	[102]
Port fuel injection	1-cylinder, 792 cc with 24 MPa DI nozzle open pressure diesel engine with 18.5:1 compression ratio	0.5 MPa port injector was mounted 0.35 m prior to the intake valve at 285° CA BTDC	The partial equivalence ratio of port injected fuel had a significant role in the progress of combustion and affected CO emissions	[103]
Port fuel injection + vaporises	1-cylinder, 661.45 cc DI diesel engine with 18:1 compression ratio	Up to 4 bars PFI supplied the fuel to the 740 W vaporiser	Higher brake thermal efficiency and reduced NOx and smoke opacity were achieved as a result of improved homogenisation of the mixture.	[104]
Early direct injection	4-cylinder inline, naturally aspirated diesel engine with 17.5:1 compression ratio	6 mg of fuel was injected with injection timing being varied from 40° to 80° BTDC. Injection pressure was also varied from 60 to 160 MPa.	Increasing the injection pressure and advancing the injection timing could reduce the HC and CO emissions induced by wall wetting.	[82]
Late direct injection	3-cylinder, 2647 cc, inline turbocharger intercooled (TCI) DI diesel engine with 15.3 compression ratio	7- and 10-hole injector were used and compared	Proposed a direct quantification to measure the homogeneity mixture of HCCI engines.	[105]
Early + late direct injection	1-cylinder, 708 cc DI diesel engine with 16:1 compression ratio	300 bar nozzle opening pressure with 5 injector holes was used to inject fuel at early (45° BTDC) and late timing (10° BTDC)	Early injection gave more homogeneous mixture because the start of combustion angle delay was nearly two times than that of late injection.	[106]
Two-stage direct injection (TSDI)	1-cylinder, naturally aspirated diesel engine with 17:1 compression ratio	First injection was varied at the intake stroke, while the second injection was varied at the end of the compression stroke	The second injection had a more profound effect in changing the peak pressure than the first injection	[107]
Two-stage direct injection (TSDI)	1-cylinder, naturally aspirated diesel engine with 17:1 compression ratio	First injection was fixed at the intake stroke, while the second injection was varied close to the compression stroke TDC	By changing the second injection timing, the combustion phasing could be controlled effectively	[108]
Multiple pulse injection	4-cylinder, 2200 common rail diesel engine with 17.2:1 compression ratio	Solenoid injector, mini Sac nozzle type with 6 holes and 1600 bar of max injection pressure was used to inject diesel fuel in five time pulses.	Compared to a single pulse, multiple pulse injection gave lower emissions and high thermal efficiency.	[109]

METHODS TO CONTROL AUTO-IGNITION

Theoretically, there are two ways to control the combustion phasing of an HCCI engine; controlling the reactivity of the mixture and the temperature evolution. However, in reality, a number of methods can be used. This includes controlling the temperature of the intake charge, changing the composition of the intake charge and modifying the gas temperature during the compression. Figure 9 summarises the methods to control HCCI combustion phasing. The idea of HCCI combustion is to offer improved performance and reduced emissions through the homogenisation of the mixture. The homogeneous charge then results in simultaneous fuel burns and very fast combustion observed at multiple locations in the cylinder. However, the combustion occurs so fast that it can lead to knocking before the medium load is even reached. Therefore, it is important to control its combustion phasing. This is the focus discussion in this section. In general, there are three methods to control HCCI combustion phasing: (1) controlling intake temperature, (2) changing intake composition and (3) modifying the gas temperature.

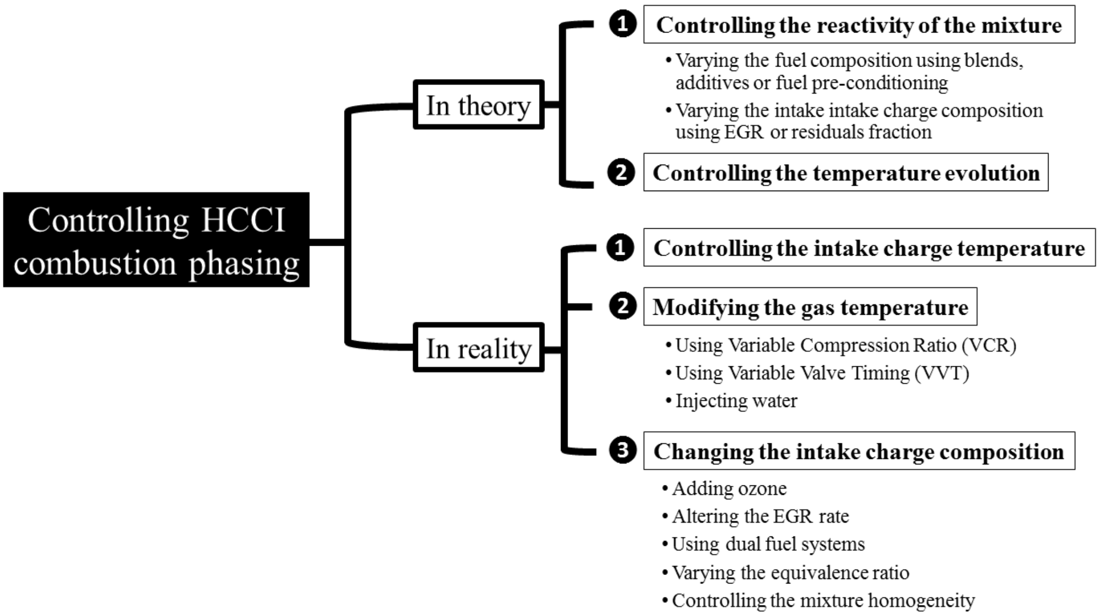

Figure 9. Methods to control HCCI combustion phasing.

Controlling Intake Charge Temperature

The inlet air temperature is one of the main engine parameters that can control HCCI combustion. The most straightforward method to control the intake temperature is by heating the intake of fresh air. In the previous section, it is used to help the evaporation of diesel fuel. However, it is important to remember that combustion can be sensitive to intake temperature changes. This is because the intake temperature affects significantly the chemical reactions of low-temperature and negative temperature coefficient (NTC) phases.

It is generally known that the use of diesel-like fuel such as n-heptane in HCCI engines undergoes three oxidation phases: (1) low temperature, (2) NTC and (3) high temperature [110]. The profound influence of intake temperature on the first two phases will significantly influence the whole combustion performance. Increasing the intake temperature may shorten the auto-ignition delay, thus causing early ignition. Low intake air temperature may be sufficient to ignite the richer mixture up to $\lambda = 2$. Leaner mixture (above $\lambda = 5$) may be ignited by increasing the intake air temperature. However, higher intake air temperature and rich mixture tend to cause knocking with a very high-pressure rise rate. Also, the early ignition can result in negative engine work. Consequently, the COV of P_{max} will increase with the increase of intake air temperature, while the COV of IMEP will decrease.

The intake air temperature may have a major effect on the peak in-cylinder pressure and its position as well as the heat release rate and maximum rate of pressure rise. It may also affect thermal and combustion efficiency. Besides heating the intake air, a diesel fuel vaporiser can also be a promising strategy to form a homogeneous mixture in the intake system. The diesel vapour induction may reduce the ignition delay and emissions. All the drawbacks mentioned above, such as knocking tendency, high HC and CO emissions as well as noise problems, have hindered the development of PFI HCCI combustion despite its benefits in terms of reduced NOx and PM emissions. This is due to a problem in its fuel evaporation and combustion phasing control that narrows its operating range. Stable HCCI combustion can be achieved by varying intake air temperature for different air-fuel ratios. Bendu and Sivalingam [111] investigated the effect of intake temperature on HCCI engines fuelled with ethanol. The results showed that the intake air temperature had a profound effect on in-cylinder pressure, ringing intensity, combustion efficiency, thermal efficiency and emissions. The combustion efficiency and brake thermal efficiency were at their maximum values at 170 ºC intake air temperature. Furthermore, ultra-low smoke emission was observed, while the NO emission was below 11 ppm. However, HC and CO emissions were higher.

Gowthaman and Sathiyagnanam [112] varied the inlet air temperature from 90 to 150 ºC. It was found that with the increase of intake temperature, the power output and NOx emissions increased, while the HC, CO, smoke emission and specific fuel consumption reduced. In terms of the pressure of the port injection system, The same authors in another study [113] investigated the influence of fuel injection pressure and charge temperature on HCCI engine. The injection pressure in the port fuel injector was varied from 3 bar to 5 bar, while the inlet air temperatures are varied from 40 ºC to 70 ºC. The results showed that 5 bar injection pressure and 60 ºC air temperature was able to achieve the brake thermal efficiency comparable to that of a conventional diesel engine, with both NOx and smoke emissions being reduced significantly. Although increasing the inlet air temperature improves the vaporisation of diesel fuel, it was found that the operation range of the HCCI engine was limited by the high knocking intensity and NOx emissions at higher inlet temperature. Furthermore, the pressure of fuel injection was also limited due to high HC and NOx emissions.

Singh and Agarwal [114] used an electrically heated fuel vaporiser to achieve a homogeneous mixture and control the combustion phasing of HCCI engine fuelled with biodiesel-diesel blends. The intake charge temperature was varied; 160

ºC, 180 ºC and 200 ºC at different engine loads. High intake air temperature improved the combustion characteristics and reduced the HC, CO and PM emissions. However, higher intake air temperature led to excessive knocking, thus deteriorating the engine performance. Furthermore, it also increased the NOx emissions at high loads. At higher engine loads, a slight tendency of knocking also increased.

Modifying Gas Temperature

The variable compression ratio (VCR) and variable valve timing (VVT) can be used to modify gas temperature inside the cylinder as a way to control the combustion phasing of the HCCI engine. However, VVT is often used in HCCI gasoline engine, therefore only VCR is covered in this section. The use of VCR can control the temperature and pressure of the mixture by adjusting the compression ratio. At low loads, a higher ratio is preferable to avoid misfire by providing more energy. At high loads, a lower ratio is favourable to slow down the combustion and prevent knock. It is important to note that although reducing the compression ratio can solve the early autoignition problem, the efficiency will undoubtedly suffer significantly from the lower compression ratio. However, in general, the HCCI operation range can be extended by controlling its combustion phasing using VCR.

Christensen, Hultqvist and Johansson [115] modified a cylinder head of diesel engine to achieve VCR, enabling a change of the compression ratio. Various mixtures of gasoline and diesel fuel were used, and the experiment was conducted with a constant equivalence ratio of 3. It was found that by using a variable compression ratio, any fuel could be used in the HCCI engine. As the compression ratio increased, the combustion efficiency decreased. Therefore, the indicated efficiency did not linearly increase with the increase of compression ratio. Furthermore, the NOx and HC emissions were very low and high, respectively, as the compression ratio increased.

In another study by the same research group, Haraldsson et al. [116] used variable compression ratio to change the compression temperature so that HCCI combustion phasing can be controlled. The isooctane/n-heptane is used as the primary reference fuel. With a fuel of RON 60, the maximum speed of 5000 rpm was achieved. Furthermore, at a maximum load of 4.4 bar BMEP for 2000 rpm, brake thermal efficiency reached 33%. Different results were obtained by Olsson et al. [117]. They used a piston with interchangeable flat steel crowns to enable different compression ratios of 21:1, 20:1, 17:1 and 15:1. In terms of its ability to delay the ignition timing, the results showed that different compression ratios had no major impact. The heat release rate was also slightly affected. However, it was found that at a higher compression ratio, the peak cylinder pressure was higher and NOx emissions were lower.

Changing the Intake Charge Composition

To control the HCCI combustion phasing by changing its intake charge composition can be achieved using several methods. This includes altering the exhaust gas recirculation (EGR) rate [118-120], adding ozone [121, 122], varying the equivalence ratio [123] and using dual fuel systems [124-127]. One of the most common methods to change the intake composition of the HCCI engine is by recirculating the exhaust gas into the intake manifold. This method is known as EGR. In a conventional diesel engine, EGR is used to reduce NOx emissions [128-130], but in an HCCI engine, it is used to control the combustion phasing [131]. EGR can be used to control the autoignition of the HCCI engine; the EGR was used to decrease the heat release rate and control knock. While the diesel engine produces relatively higher soot and NOx emissions, the HCCI engine produces no soot emissions and a very small amount of NOx emissions. Therefore, without the use of EGR, NOx is already lower in the HCCI engine compared to the conventional engine such as a diesel engine. With the help of EGR, quench can be avoided thus resulting in even lower temperature combustion so that NOx can be reduced more significantly in HCCI engine [119].

The use of EGR on the HCCI engine is considered an effective way to control its combustion phasing and can potentially reduce the NOx and PM simultaneously [119]. However, using the dilution effect by employing EGR as a way to delay the ignition and reduce the excessive in-cylinder pressure of HCCI engine is problematic. The problems include misfire, unstable combustion and low power output. Moreover, the use of EGR also raises the HC and CO emissions. To achieve better performance and low emissions, high-octane fuels and high-cetane fuels can be used together. High-octane fuels such as hydrogen offer high knock resistance, while high-cetane fuels give a shorter ignition delay, thus allowing more time to complete the combustion [132]. It can also reduce both HC and CO emissions simultaneously [133]. Furthermore, hydrogen also has a wide range of flammability limits enabling the engine to run with a lean mixture with a high amount of excess air [134, 135].

Hydrogen is growing its popularity as an important renewable fuel to meet future energy demands [136-138]. It provides ultra-low emissions, high efficiency, high burning velocity, long-term availability and a high heating value and diffusivity [132]. When hydrogen reacts with pure oxygen, only water is produced, thus eliminating CO_2 emissions. Furthermore, the combustion of hydrogen does not also lead to ozone layer depletion and acid rain. Nearly no CO and HC emissions are produced when hydrogen is used in an internal combustion engine. A small portion of those two emissions is caused by lubrication oil burning in the cylinder wall.

Hydrogen is preferable to be used in SI engines than in CI engines [139]. This is because a diesel engine cannot burn hydrogen as a sole fuel since the compression temperature is not sufficient for combustion to occur. Hydrogen has a self-ignition temperature of 858 K, thus requiring spark plugs to assist the combustion [132]. Therefore, hydrogen is more suitable for the SI engine. However, hydrogen can be used in dual-fuel operation in CI engine where the gaseous fuel is inducted or injected and mixed with air. This mixture is then ignited by diesel fuel that is compressed inside the cylinder.

Due to its high self-ignition temperature, hydrogen is not easily compressed using the direct injection method. A number of methods have been proposed to induct hydrogen into the inlet manifold and mix it with air. However, the high quantity of hydrogen cannot be added since it will replace air and consequently reduce the amount of oxygen for combustion. Moreover, hydrogen cannot be used as a pure fuel in HCCI engine due to its knocking problem at high engine load. However, it can be used as an additive on HCCI engine to control the combustion phasing and to enhance the engine performance as well as reduce emissions [140].

Table 2. Recent studies employing various methods to control auto-ignition for HCCI combustion in diesel engine.

Methods	Base engine	Major findings	Refs.
Pre-heater	1-cylinder, naturally aspirated, 273 cc DI diesel engine, CR = 20:1	The minimum temperature to obtain stable HCCI combustion was 25 °C for a compression ratio of 20:1.	[141]
Pre-heater	1-cylinder, 661 cc water cooled diesel engine, CR = 17.5:1	Heated inlet air improved the vaporisation of diesel fuel, but it limited the HCCI engine operating range.	[113]
Pre-heater + ethanol	1-cylinder, 661 cc air cooled diesel engine, CR = 17.5:1	At 170 °C inlet air temperature, BTE peaked at 43%. The BTE increased and exhaust gas temperature decreased with higher inlet air temperature.	[111]
Pre-heater + ethanol	1-cylinder, 661 cc air cooled diesel engine, CR = 17.5:1	Relatively insignificant NOx and smoke were produced using port-injected ethanol.	[142]
Variable compression ratio	1-cylinder, naturally aspirated, 273 cc DI diesel engine, CR = 20:1	Decreasing compression ratio from 20:1 to 14.87:1 could extend the operating range of HCC engine (from 2400 to 3200 rpm and 30% to 50% load).	[141]
Water addition	1-cylinder, 612 cc diesel engine with variable compression ratio	Water could control the combustion phasing of the HCCI engine by delaying the start of combustion and reducing peak cylinder pressure and heat release rate.	[143]
Ozone	1-cylinder, 103.3 cc diesel engine, CR = 16.5:1	O3 molecules accelerated the ignition and increased the released of mass-specific energy in HCCI combustion.	[121]
EGR	1-cylinder, 950 cc diesel engine, CR = 17.5:1	Peak cylinder pressure was reduced, and combustion phasing could be retarded using EGR.	[144]
EGR	1-cylinder, 2147 cc DI diesel engine, CR = 14.8:1	Early and tool late EGR switching are undesirable to the smoothness of CA50	[145]
Butanol + EGR	4-cylinder, 1998 cc, common rail diesel engine, CR = 18.2:1	Butanol low reactivity helped to achieve optimal combustion phasing and thermal efficiencies equivalent to traditional diesel combustion (43–46%). At higher engine loads, both boost and EGR are required to reduce high-pressure levels and adjust the start of the combustion cycle to obtain high thermal efficiency.	[102]
EGR + boosting	1-cylinder, 498 cc diesel engine, CR = 14.5:1	EGR and boosting reduced pressure rise rate by slowing down the decomposition of hydrogen peroxide in the autoignition process.	[120]
Varying injection pressure, EGR and intake pressure	1-cylinder, 2147 cc diesel engine with simulated boosting control, CR = 14.8:1	Injection pressure greatly affected the cycle variations in IMEP and P_{max}. EGR could be used to decrease engine emission, but higher EGR rate resulted in the leaner mixture and unstable combustion, thus affecting the cycle to cycle variations. Increasing intake pressure (boosting) was found to reduce the heat release rate and could be used to extend the operating load of the HCCI engine.	[146]

In addition to the use of EGR and hydrogen, using one of the most oxidising chemical species such as ozone (O_3) has emerged as a method to control the HCCI combustion phasing. The ozone is seeded at the intake of an HCCI engine. The ozonisers are increasingly becoming smaller, allowing them to be installed in a car. Masurier et al. [147] investigated the HCCI engine with ozone seeding in the intake. It was found that combustion phasing was advanced with the addition of ozone. The ozone assisted the ignition at temperatures where the mixture without ozone did not ignite. In another study, Pinazzi et al. [148] investigated the effects of ozone seeding in the HCCI engine. The results showed that the ozone seeding improved the engine efficiencies and extended the HCCI operating range towards low temperatures. Masurier et al. [149] applied ozone to the HCCI engine to control the combustion of three alcohol fuels: methanol, ethanol and n-butanol. It was found that ozone was beneficial to control the combustion phasing of alcohol fuels in the HCCI engine. It improved combustion and advanced its phasing. Butanol was more affected by the ozone seeding compared to methanol and ethanol. By changing the ozone concentration, HCCI combustion parameters were successfully controlled. The kinetics results revealed that alcohol fuels were initially oxidised by O-atoms.

Schönborn et al. [150] changed the fuel molecular structure using a chemical reaction with ozone before the fuel entered the combustion chamber. This approach was proposed to control the time ignition of the mixture. Ozone was produced using air and a corona discharge ozoniser. The ozone reacted with the fuel in a reaction chamber prior to its injection into the engine. The results showed that the fuel that had previously reacted with ozone ignited earlier due to its molecular structure changes compared to that without ozone. This study indicates that the time of ignition of the HCCI engine can be controlled by maintaining constant value other engine parameters such as the load, speed, pressure and intake air temperature.

Foucher et al. [151] investigated the effect of ozone on the combustion of n-heptane in an HCCI engine. The engine parameters were kept constant at an equivalence ratio of 0.3, intake temperature of 300 K and engine speed of 1500 rpm. The ozone was produced by a dielectric barrier discharge reactor with a wire-cylinder configuration. The results showed that low ozone concentrations (<50 ppm) had a profound effect on the cool and main flame of HCCI combustion. The kinetic modelling was also conducted and found that the fuel (n-heptane/n-C_7H_{16}) began to oxidise by reacting with O-atoms produced by ozone decomposition (n-$C_7H_{16} + O \rightarrow C_7H_{15} + OH$). As a result, OH was produced with its production being accelerated by the ozone reaction. The OH then speed up both cool and main flame of combustion. This study has revealed that the use of ozone can be used to control the combustion phasing of the HCCI engine. To conclude for this section, some important recent studies to control auto-ignition for HCCI combustion in the diesel engine are shown in Table 2.

CONCLUSION AND FUTURE RESEARCH DIRECTIONS

HCCI is a promising concept employing the approach of premixed combustion to ensure the homogeneous and lean mixture under autoignition event. The combustion occurs at multiple locations in the chamber, resulting in no flame front, thus reducing the local temperatures. Consequently, the NOx formation is reduced to a near-zero level. In addition to ultra-low NOx emissions due to its homogeneous mixture, by maintaining the local fuel-air ratio to be low, the soot formation normally resulted from heterogeneous flames of diesel engine, can also be avoided.

One of the main challenges in HCCI combustion is to form a homogeneous mixture. In order to have the homogeneous charge, a significant amount of time is needed. The PFI system is one of the easiest methods to use and is considered as the ideal HCCI combustion. However, both the evaporation process and autoignition control of diesel fuel remains the biggest challenge. This is because diesel fuel has low volatility and high cetane number. Consequently, the efficiency and operation range of PFI HCCI diesel engines are limited. Moreover, the noise and unburned hydrocarbon emissions are also still high. Therefore, although PFI HCCI combustion offers ultra-low PM and NOx emission, such a strategy needs more investigating. Some solutions have been proposed such as by combining it with direct injection systems.

Early DI HCCI diesel engine can achieve a homogeneous mixture by injecting the fuel well-advanced in the compression stroke. However, wall-wetting remains the biggest challenge since the density of the chamber when the injection occurs is low. This can lead to cylinder liner erosion and fuel interaction with oil. To solve the problem, a few research groups have been proposing using multiple injection strategies or modifying the injector configuration.

Early or multiple DI HCCI diesel engines cannot reduce the PM and NOx emissions as significant as PFI methods, but both emissions are still far below compared to those of conventional diesel engines. Interestingly, the late injection combined with high EGR rates may be the simplest solution to achieve HCCI combustion. To achieve that, the injection should be finished during the period of autoignition delay time, and high injection rates achieved by high mixing rates are required. Compared to PFI or early DI HCCI injection, late DI allows the control of the start of combustion to be relatively easier. Furthermore, since the equipment does not require major modification, the late DI HCCI is widely adopted by numerous research groups.

All in all, the PFI, early and multiple injection strategies found in the HCCI engine can only achieve part-load operating conditions. The mass production of the HCCI engine remains the biggest challenge. To expand the operating range of HCCI combustion, the improvement of combustion control strategies is a must. To control its combustion timing and reduce its high HC and CO emissions, several strategies were successfully applied to indirectly control its combustion phasing, such as the use of pre-heater, VCR and EGR. Fuel is also one of the important parameters to extend the operating range of an HCCI engine. Fuel modification, i.e. the development of more appropriate fuel formations by modifying its physical properties and/or chemical composition, plays an essential role to improve the HCCI engine operation.

Finally, the development of vehicle technology such as advanced boosting, variable valve actuation, variable compression ratio and novel injection system can bring the HCCI concept to the next level. It is important to note that the strategies to form a homogeneous mixture can also be used to control HCCI auto-ignition or vice versa. In the meantime, the most viable approach would be using a dual system where conventional diesel and HCCI combustion are employed together. The conventional diesel is used for full load conditions, while the HCCI is for low and part-load conditions.

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REFERENCES

[1] M. Dehghani Madvar *et al.*, "Current status and future forecasting of biofuels technology development," *Int. J. Energy Res.,* vol. 43, no. 3, pp. 1142-1160, 2019.

[2] F. S. Mirhashemi and H. Sadrnia, "NOX emissions of compression ignition engines fueled with various biodiesel blends: A review," *J. Energy Inst.,* 2019.

[3] T. Grigoratos *et al.*, "Real world emissions performance of heavy-duty Euro VI diesel vehicles," *Atmos. Environ.,* vol. 201, pp. 348-359, 2019.

[4] I. Veza *et al.*, "Effect of COVID-19 on biodiesel industry: A case study in Indonesia and Malaysia," *Int. J. Automot. Mech. Eng.,* vol. 18, no. 2, pp. 8637-8646, 2021.

[5] N. Sharma and A. K. Agarwal, "Effect of fuel injection pressure and engine speed on performance, emissions, combustion, and particulate investigations of gasohols fuelled gasoline direct injection engine," *J. Energy Resour. Technol.,* vol. 142, no. 4, 2020.

[6] B. Giechaskiel *et al.*, "European regulatory framework and particulate matter emissions of gasoline light-duty vehicles: A review," *Catalysts,* vol. 9, no. 7, p. 586, 2019.

[7] A. Katijan *et al.*, "An experimental study for emission of four stroke carbureted and fuel injection motorcycle engine," *J. Adv. Res. Fluid Mech. Therm. Sci.,* vol. 62, no. 2, pp. 256-264, 2019.

[8] I. Veza, M. Said, and Z. Latiff, "Improved performance, combustion and emissions of si engine fuelled with butanol: A review," *Int. J. Automot. Mech. Eng.,* vol. 17, no. 1, pp. 7648-7666, 2020.

[9] P. Shihabudeen *et al.*, "Ceria-based mixed oxide nanoparticles for diesel engine emission control," in *Advanced Engine Diagnostics*: Springer, 2019, pp. 143-163.

[10] S. Nag *et al.*, "Experimental study of engine performance and emissions for hydrogen diesel dual fuel engine with exhaust gas recirculation," *Int. J. Hydrogen Energy,* vol. 44, no. 23, pp. 12163-12175, 2019.

[11] M. N. A. Mukhtar *et al.*, "Tri-fuel emulsion with secondary atomization attributes for greener diesel engine – A critical review," *Renew. Sust. Energ. Rev.,* vol. 111, pp. 490-506, 2019/09/01/ 2019.

[12] V. V. Pham and D. T. Cao, "A brief review of technology solutions on fuel injection system of diesel engine to increase the power and reduce environmental pollution," *Journal of Mechanical Engineering Research & Developments (JMERD),* vol. 42, no. 1, pp. 1-9, 2019.

[13] E. Neshat, M. Nazemian, and D. Honnery, "Thermodynamic modeling and validation of in-cylinder flow in diesel engines," *Environ. Prog. Sustain. Energy,* 2019.

[14] S. V. Khandal *et al.*, "Paradigm shift from mechanical direct injection diesel engines to advanced injection strategies of diesel homogeneous charge compression ignition (HCCI) engines- A comprehensive review," *Renew. Sust. Energ. Rev.,* vol. 70, pp. 369-384, 2017/04/01/ 2017.

[15] I. Veza, M. F. M. Said, and Z. A. Latiff, "Progress of acetone-butanol-ethanol (ABE) as biofuel in gasoline and diesel engine: A review," *Fuel Process. Technol.,* vol. 196, p. 106179, 2019/12/15/ 2019.

[16] F. M. Hossain, M. N. Nabi, and R. J. Brown, "Investigation of diesel engine performance and exhaust emissions of microalgae fuel components in a turbocharged diesel engine," *Energy Convers. Manage.,* vol. 186, pp. 220-228, 2019.

[17] N. S. Ekaab, N. H. Hamza, and M. T. Chaichan, "Performance and emitted pollutants assessment of diesel engine fuelled with biokerosene," *Case Studies in Thermal Engineering,* vol. 13, p. 100381, 2019.

[18] S. Li *et al.*, "Experimental study on combustion and emission characteristics of a diesel engine fueled with diesel-gasoline-iso-butanol blends," *Fuel,* vol. 255, p. 115761, 2019.

[19] D. Needham *et al.*, "Dynamic rate shaping–one diesel common-rail injector for all combustion strategies," in *Heavy-Duty-, On-und Off-Highway-Motoren 2018*: Springer, 2019, pp. 335-357.

[20] P. Vijayashree and V. Ganesan, "Oxygenated fuel additive option for PM emission reduction from diesel engines—A review," in *Engine Exhaust Particulates*: Springer, 2019, pp. 141-163.

[21] V. Chaudhary and R. Gakkhar, "Exergy based performance comparison of DI diesel engine fuelled with WCO15 and NEEM15 biodiesel," *Environ. Prog. Sustain. Energy,* 2019.

[22] G. Gonca and B. Sahin, "Performance analysis of a novel eco-friendly internal combustion engine cycle," *Int. J. Energy Res.,* vol. 43, no. 11, pp. 5897-5911, 2019.

[23] I. Veza *et al.*, "Physico-chemical properties of Acetone-Butanol-Ethanol (ABE)-diesel blends: Blending strategies and mathematical correlations," *Fuel,* vol. 286, p. 119467, 2021/02/15/ 2021.

[24] I. Veza, M. F. Muhamad Said, and Z. A. Latiff, "Recent advances in butanol production by acetone-butanol-ethanol (ABE) fermentation," *Biomass Bioenergy,* vol. 144, p. 105919, 2021/01/01/ 2021.

[25] A. T. Mohammed *et al.*, "Soil fertility enrichment potential of Jatropha curcas for sustainable agricultural production: A case study of Birnin Kebbi, Nigeria," *Annals of the Romanian Society for Cell Biology,* pp. 21061-21073, 2021.

[26] I. Veza *et al.*, "Application of Elman and Cascade neural network (ENN and CNN) in comparison with adaptive neuro fuzzy inference system (ANFIS) to predict key fuel properties of ABE-diesel blends," *Int. J. Green Energy,* pp. 1-13, 2021.

[27] M. Rusli *et al.*, "Performance and Emission Measurement of a Single Cylinder Diesel Engine Fueled with Palm Oil Biodiesel Fuel Blends," in *IOP Conference Series: Materials Science and Engineering*, 2021, vol. 1068, no. 1, p. 012020: IOP Publishing.

[28] I. Veza *et al.*, "Cetane index prediction of ABE-diesel blends using empirical and artificial neural network models," *Energy Sources A: Recovery Util. Environ. Eff.,* pp. 1-18, 2020.

[29] A. Kontses *et al.*, "Effects of fuel properties on particulate emissions of diesel cars equipped with diesel particulate filters," *Fuel,* vol. 255, p. 115879, 2019.

[30] J. Fang *et al.*, "The effect of operating parameters on regeneration characteristics and particulate emission characteristics of diesel particulate filters," *Appl. Therm. Eng.,* vol. 148, pp. 860-867, 2019.

[31] H. Kong and K. Yamamoto, "Simulation on soot deposition in in-wall and on-wall catalyzed diesel particulate filters," *Catal. Today,* vol. 332, pp. 89-93, 2019.

[32] J. Li *et al.*, "Effects of different diesel particulate filter on emission characteristics of in-use diesel vehicles," *Energy Sources A: Recovery Util. Environ. Eff.,* pp. 1-12, 2019.

[33] H. Wang *et al.*, "Ash deposited in diesel particular filter: a review," *Energy Sources A: Recovery Util. Environ. Eff.,* vol. 41, no. 18, pp. 2184-2193, 2019.
[34] N. R. Brodnik and K. T. Faber, "Out-of-plane mechanical characterization of acicular mullite and aluminum titanate diesel particulate filters," *International Journal of Applied Ceramic Technology,* vol. 16, no. 3, pp. 1173-1183, 2019.
[35] J. Zokoe, C. Su, and P. J. McGinn, "Soot combustion activity and potassium mobility in diesel particulate filters coated with a K-Ca-Si-O glass catalyst," *Ind. Eng. Chem. Res.,* 2019.
[36] E. Jiaqiang *et al.*, "Performance enhancement of microwave assisted regeneration in a wall-flow diesel particulate filter based on field synergy theory," *Energy,* vol. 169, pp. 719-729, 2019.
[37] R. Smit *et al.*, "Evaluation of real-world gaseous emissions performance of selective catalytic reduction and diesel particulate filter bus retrofits," *Environ. Sci. Technol.,* vol. 53, no. 8, pp. 4440-4449, 2019.
[38] Y. Li and S. A. Roth, "Multifunctional filters for diesel emission control," ed: Google Patents, 2019.
[39] A. Wang *et al.*, "Unraveling the mysterious failure of Cu/SAPO-34 selective catalytic reduction catalysts," *Nat. Commun.,* vol. 10, no. 1, p. 1137, 2019.
[40] Q. Jin *et al.*, "Novel TiO2 catalyst carriers with high thermostability for selective catalytic reduction of NO by NH3," *Catal. Today,* vol. 327, pp. 279-287, 2019.
[41] R. J. Nuguid *et al.*, "Modulated-excitation Raman spectroscopy of V2O5/TiO2: Mechanistic insights into the selective catalytic reduction of NO by NH3," *ACS Catalysis,* 2019.
[42] H. I. Hamoud, V. Valtchev, and M. Daturi, "Selective catalytic reduction of NOx over Cu-and Fe-exchanged zeolites and their mechanical mixture," *Applied Catalysis B: Environmental,* vol. 250, pp. 419-428, 2019.
[43] H.-Y. Chen *et al.*, "Formation of NO+ and its possible roles during the selective catalytic reduction of NOx with NH3 on Cu-CHA catalysts," *Catal. Today,* vol. 320, pp. 61-71, 2019.
[44] F. Farid, J. Gong, and V. R. Rajagopal, "Systems and methods for diagnosing selective catalytic reduction systems," ed: Google Patents, 2019.
[45] A. Punke *et al.*, "Catalyzed soot filter for use in passive selective catalytic reduction," ed: Google Patents, 2019.
[46] H.-X. Li, W. E. Cormier, and B. Moden, "High silica chabazite for selective catalytic reduction, methods of making and using same," ed: Google Patents, 2019.
[47] P. Piqueras *et al.*, "Performance of a diesel oxidation catalyst under diesel-gasoline reactivity controlled compression ignition combustion conditions," *Energy Convers. Manage.,* vol. 196, pp. 18-31, 2019.
[48] S. Hoang *et al.*, "High performance diesel oxidation catalysts using ultra-low Pt loading on titania nanowire array integrated cordierite honeycombs," *Catal. Today,* vol. 320, pp. 2-10, 2019.
[49] T. Kanerva *et al.*, "Microstructural characteristics of vehicle-aged heavy-duty diesel oxidation catalyst and natural gas three-way catalyst," *Catalysts,* vol. 9, no. 2, p. 137, 2019.
[50] A. F. Chiffey *et al.*, "Diesel oxidation catalyst and exhaust system," ed: Google Patents, 2019.
[51] C. Hengst, F. Dornhaus, and M. Schiffer, "Three-zone diesel oxidation catlayst," ed: Google Patents, 2019.
[52] S. Sung *et al.*, "Manganese-containing diesel oxidation catalyst," ed: Google Patents, 2019.
[53] P. Punov *et al.*, "Progress in high performance, low emissions, and exergy recovery in internal combustion engines," *Int. J. Energy Res.,* vol. 41, no. 9, pp. 1229-1241, 2017.
[54] I. Veza *et al.*, "Simulation of predictive kinetic combustion of single cylinder HCCI engine," in *AIP Conference Proceedings*, Pahang, Malaysia, 2019, vol. 2059, no. 1, pp. (020017-1)-(020017-9): AIP Publishing.
[55] M. Nazoktabar *et al.*, "Controlling the optimal combustion phasing in an HCCI engine based on load demand and minimum emissions," *Energy,* 2019.
[56] H. Taghavifar, A. Nemati, and J. H. Walther, "Combustion and exergy analysis of multi-component diesel-DME-methanol blends in HCCI engine," *Energy,* vol. 187, p. 115951, 2019.
[57] I. Veza *et al.*, "Potential of range extender electric vehicles (REEVS)," in *IOP Conference Series: Materials Science and Engineering*, 2020, vol. 884, no. 1, p. 012093: IOP Publishing.
[58] M. F. Roslan, I. Veza, and M. F. M. Said, "Predictive simulation of single cylinder n-butanol HCCI engine," in *IOP Conference Series: Materials Science and Engineering*, 2020, vol. 884, no. 1, p. 012099: IOP Publishing.
[59] M. Mofijur *et al.*, "Performance and emission parameters of homogeneous charge compression ignition (HCCI) engine: A review," *Energies,* vol. 12, no. 18, p. 3557, 2019.
[60] S. S. Bhurat *et al.*, "Technical barriers and their solutions for deployment of HCCI engine technologies–a review," *Int. J. Ambient Energy,* pp. 1-14, 2019.
[61] K. Venkateswarlu and K. Ramakrishna, "Effect of turbulence and multiple injection strategies on homogeneous charge compression ignition (HCCI) diesel engines–a review," *Int. J. Ambient Energy,* pp. 1-15, 2019.
[62] N. Mishra *et al.*, "Modelling of biogas fueled HCCI engine for various inlet conditions," in *International Conference on Emerging Trends in Engineering (ICETE)*, 2020, pp. 394-403: Springer.
[63] V. Chaudhari and D. Deshmukh, "Challenges in charge preparation and combustion in homogeneous charge compression ignition engines with biodiesel: A review," *Energy Reports,* vol. 5, pp. 960-968, 2019.
[64] J. Du *et al.*, "Mechanism of combustion noise influenced by pilot injection in PPCI diesel engines," *Applied Sciences,* vol. 9, no. 9, p. 1875, 2019.
[65] M. T. Chaichan, "Combustion and emission characteristics of E85 and diesel blend in conventional diesel engine operating in PPCI mode," *Thermal Science and Engineering Progress,* vol. 7, pp. 45-53, 2018.
[66] X. Cheng *et al.*, "Investigation into partially premixed combustion fueled with N-butanol-diesel blends," *Renewable energy,* vol. 86, pp. 723-732, 2016.
[67] X. Liang *et al.*, "A review of early injection strategy in premixed combustion engines," *Applied Sciences,* vol. 9, no. 18, p. 3737, 2019.
[68] F. Yang *et al.*, "Load expansion of a dieseline compression ignition engine with multi-mode combustion," *Fuel,* vol. 171, pp. 5-17, 2016.
[69] S.-Y. No, "Application of biobutanol in advanced CI engines–A review," *Fuel,* vol. 183, pp. 641-658, 2016.
[70] Y. Wang *et al.*, "A parametric study for enabling reactivity controlled compression ignition (RCCI) operation in diesel engines at various engine loads," *Appl. Energy,* vol. 175, pp. 389-402, 2016.

[71] K. Poorghasemi *et al.*, "Effect of diesel injection strategies on natural gas/diesel RCCI combustion characteristics in a light duty diesel engine," *Appl. Energy,* vol. 199, pp. 430-446, 2017.

[72] A.-H. Kakaee, P. Rahnama, and A. Paykani, "Influence of fuel composition on combustion and emissions characteristics of natural gas/diesel RCCI engine," *J. Nat. Gas Sci. Eng.,* vol. 25, pp. 58-65, 2015.

[73] J. Li, W. Yang, and D. Zhou, "Review on the management of RCCI engines," *Renew. Sust. Energ. Rev.,* vol. 69, pp. 65-79, 2017.

[74] J. Benajes *et al.*, "An investigation on the particulate number and size distributions over the whole engine map from an optimized combustion strategy combining RCCI and dual-fuel diesel-gasoline," *Energy Convers. Manage.,* vol. 140, pp. 98-108, 2017.

[75] Y. Xu *et al.*, "The effects of variable geometry turbine opening on reactivity controlled compression ignition combustion," *Environ. Prog. Sustain. Energy,* vol. 38, no. 3, 2019.

[76] R. H. Thring, "Homogeneous-charge compression-ignition (HCCI) engines," SAE Technical paper0148-7191, 1989.

[77] J. Hunicz, A. Tmar, and P. Krzaczek, "Effects of mixture stratification on combustion and emissions of boosted controlled auto-ignition engines," *Energies,* vol. 10, no. 12, p. 2172, 2017.

[78] M. Pourfallah, M. Armin, and A. A. Ranjbar, "A numerical study on the effect of thermal and charge stratification on the HCCI natural gas engine," *Int. J. Ambient Energy,* pp. 1-10, 2019.

[79] B. Wang, "Autoignition of light naphtha and its surrogates in a rapid compression machine," *Energy Science & Engineering,* vol. 7, no. 1, pp. 207-216, 2019.

[80] N. Komninos and C. Rakopoulos, "Heat transfer in hcci phenomenological simulation models: A review," *Appl. Energy,* vol. 181, pp. 179-209, 2016.

[81] H. Zhao, *HCCI and CAI engines for the automotive industry*. Elsevier, 2007.

[82] H. Yu, X. Liang, and G. Shu, "Numerical study of the early injection parameters on wall wetting characteristics of an HCCI diesel engine using early injection strategy," *International Journal of Automotive Technology,* vol. 18, no. 5, pp. 759-768, 2017/10/01 2017.

[83] Y. Takeda, N. Keiichi, and N. Keiichi, "Emission characteristics of premixed lean diesel combustion with extremely early staged fuel injection," *SAE transact.,* pp. 938-947, 1996.

[84] H. Ishii *et al.*, "Exhaust purification of diesel engines by homogeneous charge with compression ignition part 2: Analysis of combustion phenomena and NOx formation by numerical simulation with experiment," SAE Technical Paper0148-7191, 1997.

[85] A. Harada *et al.*, "The effects of mixture formation on premixed lean diesel combustion engine," SAE Technical Paper0148-7191, 1998.

[86] H. Akagawa *et al.*, "Approaches to solve problems of the premixed lean diesel combustion," *SAE transact.,* pp. 120-132, 1999.

[87] T. Hashizume *et al.*, "Combustion and emission characteristics of multiple stage diesel combustion," *SAE transact.,* pp. 548-557, 1998.

[88] T. Suzuki *et al.*, "Development of diesel combustion for commercial vehicles," *SAE transact.,* pp. 2114-2132, 1997.

[89] H. Yokota *et al.*, "A new concept for low emission diesel combustion," *SAE transact.,* pp. 1479-1490, 1997.

[90] Y. Iwabuchi *et al.*, "Trial of new concept diesel combustion system-premixed compression-ignited combustion," SAE Technical Paper0148-7191, 1999.

[91] K. Okude *et al.*, "Premixed compression ignition (PCI) combustion for simultaneous reduction of NOx and soot in diesel engine," *SAE transact.,* pp. 1002-1013, 2004.

[92] K. Akihama *et al.*, "Mechanism of the smokeless rich diesel combustion by reducing temperature," *SAE transact.,* pp. 648-662, 2001.

[93] Y. Hotta *et al.*, "Achieving lower exhaust emissions and better performance in an HSDI diesel engine with multiple injection," SAE Technical Paper0148-7191, 2005.

[94] L. Hildingsson *et al.*, "Optical diagnostics of HCCI and UNIBUS using 2-D PLIF of OH and formaldehyde," SAE Technical paper0148-7191, 2005.

[95] B. Walter and B. Gatellier, "Development of the high power NADI™ concept using dual mode diesel combustion to achieve zero NOx and particulate emissions," *SAE transact.,* pp. 779-787, 2002.

[96] P. Duret *et al.*, "Progress in diesel HCCI combustion within the European SPACE LIGHT project," *SAE transact.,* pp. 987-1001, 2004.

[97] Y. Mase *et al.*, "Nissan's new multivalve DI diesel engine series," *SAE transact.,* pp. 1537-1546, 1998.

[98] S. Kimura *et al.*, "An experimental analysis of low-temperature and premixed combustion for simultaneous reduction of NOx and particulate emissions in direct injection diesel engines," *Int. J. Engine Res.,* vol. 3, no. 4, pp. 249-259, 2002.

[99] A. W. Gray III and T. W. Ryan III, "Homogeneous charge compression ignition (HCCI) of diesel fuel," *SAE transact.,* pp. 1927-1935, 1997.

[100] S. Kimura *et al.*, "Ultra-clean combustion technology combining a low-temperature and premixed combustion concept for meeting future emission standards," *SAE transact.,* pp. 239-246, 2001.

[101] A. Wimmer *et al.*, "Potential of HCCI concepts for DI diesel engines," *Int. J. Veh. Des.,* vol. 41, no. 1-4, pp. 32-48, 2006.

[102] M. Zheng *et al.*, "Investigation of butanol-fuelled HCCI combustion on a high efficiency diesel engine," *Energy Convers. Manage.,* vol. 98, pp. 215-224, 2015/07/01/ 2015.

[103] Y. Qian *et al.*, "Octane rating effects of direct injection fuels on dual fuel HCCI-DI stratified combustion mode with port injection of n-heptane," *Energy,* vol. 111, pp. 1003-1016, 2016/09/15/ 2016.

[104] J. Ramavathu and T. R. Kota, "Combustion performance and emission characteristics on HCCI engine of waste plastic pyrolysis oil biodiesel blends with external PFI and vaporiser," *Int. J. Sustain. Eng.,* pp. 1-14, 2019.

[105] N. Ramesh and J. M. Mallikarjuna, "Evaluation of in-cylinder mixture homogeneity in a diesel HCCI engine – A CFD analysis," *Eng. Sci. Technol. an Int. J.,* vol. 19, no. 2, pp. 917-925, 2016/06/01/ 2016.

[106] J. A. V. Godiño *et al.*, "Numerical study of HCCI combustion fueled with diesel oil using a multizone model approach," *Energy Convers. Manage.,* vol. 89, pp. 885-895, 2015/01/01/ 2015.

[107] G. Coskun *et al.*, "An experimental and modeling study to investigate effects of different injection parameters on a direct injection HCCI combustion fueled with ethanol–gasoline fuel blends," *Fuel,* vol. 215, pp. 879-891, 2018/03/01/ 2018.

[108] A. Turkcan *et al.*, "Numerical and experimental investigations of the effects of the second injection timing and alcohol-gasoline fuel blends on combustion and emissions of an HCCI-DI engine," *Fuel,* vol. 219, pp. 50-61, 2018/05/01/ 2018.

[109] K. Mathivanan, J. M. Mallikarjuna, and A. Ramesh, "Influence of multiple fuel injection strategies on performance and combustion characteristics of a diesel fuelled HCCI engine – An experimental investigation," *Exp. Therm Fluid Sci.,* vol. 77, pp. 337-346, 2016/10/01/ 2016.

[110] H. Zhao, "Overview of CAI/HCCI gasoline engines," in *HCCI and CAI Engines for the Automotive Industry*: Elsevier, 2007, pp. 21-44e.

[111] H. Bendu and M. Sivalingam, "Experimental investigation on the effect of charge temperature on ethanol fueled HCCI combustion engine," *J. Mech. Sci. Technol.,* vol. 30, no. 10, pp. 4791-4799, 2016.

[112] S. Gowthaman and A. Sathiyagnanam, "Analysis the optimum inlet air temperature for controlling homogeneous charge compression ignition (HCCI) engine," *Alexandria engineering journal,* 2017.

[113] S. Gowthaman and A. Sathiyagnanam, "Effects of charge temperature and fuel injection pressure on HCCI engine," *Alexandria Engineering Journal,* vol. 55, no. 1, pp. 119-125, 2016.

[114] A. P. Singh and A. K. Agarwal, "Effect of intake charge temperature and EGR on biodiesel fuelled HCCI engine," SAE Technical Paper0148-7191, 2016.

[115] M. Christensen, A. Hultqvist, and B. Johansson, "Demonstrating the multi fuel capability of a homogeneous charge compression ignition engine with variable compression ratio," *SAE transact.,* pp. 2099-2113, 1999.

[116] G. Haraldsson *et al.*, "HCCI combustion phasing in a multi cylinder engine using variable compression ratio," *SAE transact.,* pp. 2654-2663, 2002.

[117] J.-O. Olsson *et al.*, "Compression ratio influence on maximum load of a natural gas fueled HCCI engine," *SAE transact.,* pp. 442-458, 2002.

[118] S. Bhaduri, H. Jeanmart, and F. Contino, "EGR control on operation of a tar tolerant HCCI engine with simulated syngas from biomass," *Appl. Energy,* vol. 227, pp. 159-167, 2018.

[119] M. Nishi, M. Kanehara, and N. Iida, "Assessment for innovative combustion on HCCI engine by controlling EGR ratio and engine speed," *Appl. Therm. Eng.,* vol. 99, pp. 42-60, 2016.

[120] Y. Putrasari, N. Jamsran, and O. Lim, "An investigation on the DME HCCI autoignition under EGR and boosted operation," *Fuel,* vol. 200, pp. 447-457, 2017/07/15/ 2017.

[121] A. Starik, A. Korobov, and N. Titova, "Combustion improvement in HCCI engine operating on synthesis gas via addition of ozone or excited oxygen molecules to the charge: Modeling study," *Int. J. Hydrogen Energy,* vol. 42, no. 15, pp. 10475-10484, 2017.

[122] M. M. Salahi and A. Gharehghani, "Control of combustion phasing and operating range extension of natural gas PCCI engines using ozone species," *Energy Convers. Manage.,* vol. 199, p. 112000, 2019.

[123] P. Das *et al.*, "Effect of injection timing, premixed equivalence ratio and EGR on combustion characteristics of an HCCI-DI combustion engine using in-cylinder dual injection strategy," SAE Technical Paper0148-7191, 2016.

[124] Y. Liu *et al.*, "Ion current signal and characteristics of ethanol/gasoline dual fuel HCCI combustion," *Fuel,* vol. 166, pp. 42-50, 2016.

[125] G. R. Gawale and G. N. Srinivasulu, "Experimental investigation of ethanol/diesel and ethanol/biodiesel on dual fuel mode HCCI engine for different engine load conditions," *Fuel,* p. 116725, 2019.

[126] S. Hiremath *et al.*, "Comparative analysis of performance of dual fuel (DF) and homogeneous charge compression ignition (HCCI) engines fuelled with honne oil methyl ester (HOME) and compressed natural gas (CNG)," *Fuel,* vol. 196, pp. 134-143, 2017.

[127] G. R. Gawale and G. Naga Srinivasulu, "Numerical and experimental investigations on a dual fuel HCCI engine by using ethanol as primary fuel and diesel as secondary fuel for NOX reduction and better performance," *Int. J. Ambient Energy,* pp. 1-10, 2018.

[128] P. Zhang *et al.*, "Experimental investigation on NOx and PM pollutions of a common rail diesel diesel engine fueled with diesel/gasoline/isopropanol blends," *Sustain. Energy Fuels,* 2019.

[129] A. Bragadeshwaran *et al.*, "Influence of injection timing and exhaust gas recirculation (EGR) rate on lemon peel oil–fuelled CI engine," *Environ. Sci. Pollut. Res.,* pp. 1-15, 2019.

[130] D. R. Vallapudi *et al.*, "Combined impact of EGR and injection pressure in performance improvement and NOx control of a DI diesel engine powered with tamarind seed biodiesel blend," *Environ. Sci. Pollut. Res.,* vol. 25, no. 36, pp. 36381-36393, 2018.

[131] N. Jamsran and O. Lim, "Effects of EGR and boosting on the auto-ignition characteristics of HCCI combustion fueled with natural gas," *J. Nat. Gas Sci. Eng.,* vol. 35, pp. 1015-1024, 2016.

[132] I. Yilmaz and M. Gumus, "Effects of hydrogen addition to the intake air on performance and emissions of common rail diesel engine," *Energy,* vol. 142, pp. 1104-1113, 2018.

[133] H. A. Alrazen *et al.*, "A review of the effect of hydrogen addition on the performance and emissions of the compression–Ignition engine," *Renew. Sust. Energ. Rev.,* vol. 54, pp. 785-796, 2016.

[134] B. Zhang, C. Ji, and S. Wang, "Investigation on the lean combustion performance of a hydrogen-enriched n-butanol engine," *Energy Convers. Manage.,* vol. 136, pp. 36-43, 2017.

[135] X. Yu *et al.*, "Research on cycle-by-cycle variations of an SI engine with hydrogen direct injection under lean burn conditions," *Appl. Therm. Eng.,* vol. 109, pp. 569-581, 2016.

[136] J. Pan *et al.*, "Effect of different hydrogen blending ratios on combustion process of gasoline-fueled rotary engine," *Environ. Prog. Sustain. Energy,* 2019.

[137] R. Rath *et al.*, "Recent advances, unsolved deficiencies, and future perspectives of hydrogen fuel cells in transportation and portable sectors," *Int. J. Energy Res.,* vol. 43, no. 15, pp. 8931-8955, 2019/12/01 2019.

[138] M. Ghazvini *et al.*, "Geothermal energy use in hydrogen production: A review," *Int. J. Energy Res.,* vol. 43, no. 14, pp. 7823-7851, 2019.

[139] V. Chintala and K. Subramanian, "A comprehensive review on utilization of hydrogen in a compression ignition engine under dual fuel mode," *Renew. Sust. Energ. Rev.,* vol. 70, pp. 472-491, 2017.
[140] R. K. Maurya and N. Akhil, "Development of a new reduced hydrogen combustion mechanism with NOx and parametric study of hydrogen HCCI combustion using stochastic reactor model," *Energy Convers. Manage.,* vol. 132, pp. 65-81, 2017.
[141] T. Anh *et al.*, "Experimental Investigation on Establishing the HCCI Process Fueled by N-Heptane in a Direct Injection Diesel Engine at Different Compression Ratios," *Sustainability,* vol. 10, no. 11, p. 3878, 2018.
[142] H. Bendu, B. B. V. L. Deepak, and S. Murugan, "Multi-objective optimization of ethanol fuelled HCCI engine performance using hybrid GRNN–PSO," *Appl. Energy,* vol. 187, pp. 601-611, 2017/02/01/ 2017.
[143] M. F. Ahari and E. Neshat, "Advanced analysis of various effects of water on natural gas HCCI combustion, emissions and chemical procedure using artificial inert species," *Energy,* vol. 171, pp. 842-852, 2019/03/15/ 2019.
[144] P. Das, P. M. V. Subbarao, and J. P. Subrahmanyam, "Control of combustion process in an HCCI-DI combustion engine using dual injection strategy with EGR," *Fuel,* vol. 159, pp. 580-589, 2015/11/01/ 2015.
[145] M. Xu, Y. Gui, and K.-y. Deng, "Fuel injection and EGR control strategy on smooth switching of CI/HCCI mode in a diesel engine," *J. Energy Inst.,* vol. 88, no. 2, pp. 157-168, 2015/05/01/ 2015.
[146] S. You-cheng *et al.*, "Effects of injection pressure, exhaust gas recirculation and intake pressure on the cycle-to-cycle variations of HCCI combustion," *J. Energy Inst.,* vol. 89, no. 2, pp. 293-301, 2016/05/01/ 2016.
[147] J.-B. Masurier *et al.*, "Towards HCCI Control by Ozone Seeding," SAE Technical Paper0148-7191, 2013.
[148] P. M. Pinazzi *et al.*, "Towards stoichiometric combustion in HCCI engines: effect of ozone seeding and dilution," SAE Technical Paper0148-7191, 2015.
[149] J.-B. Masurier *et al.*, "Ozone applied to the homogeneous charge compression ignition engine to control alcohol fuels combustion," *Appl. Energy,* vol. 160, pp. 566-580, 2015.
[150] A. Schönborn *et al.*, "Ignition control of homogeneous-charge compression ignition (HCCI) combustion through adaptation of the fuel molecular structure by reaction with ozone," *Fuel,* vol. 89, no. 11, pp. 3178-3184, 2010.
[151] F. Foucher *et al.*, "Influence of ozone on the combustion of n-heptane in a HCCI engine," *Proc Combust Inst* . vol. 34, no. 2, pp. 3005-3012, 2013.