

A REVIEW ON HOMOGENEOUS CHARGE COMPRESSION IGNITION ENGINE PERFORMANCE USING BIODIESEL–DIESEL BLEND AS A FUEL

M.M. Hasan, M.M. Rahman, and K. Kadirgama

Faculty of Mechanical Engineering, Universiti Malaysia Pahang
26600 Pekan, Pahang, Malaysia
E-mail: mustafizur@ump.edu.my
Phone: +6094246239; Fax: +6094246222

ABSTRACT

Homogeneous charge compression ignition (HCCI) engines employ a relatively new mode of combustion technology, in which auto-ignition occurs when the lean mixture of air and fuel reaches its chemical activation energy. It is a combustion concept that offers simultaneous reductions in both NO_x and soot emissions from internal combustion engines. A wide range of fuels can be used in this engine. Of these, diesel and biodiesel–diesel blends are most common. The objective of this study is to illustrate the fuel properties, engine performance and emission characteristics of the mentioned fuels at different conditions performed worldwide in HCCI engines, as well as to compare HCCI engines with conventional compression ignition (CI) engines in respect of engine combustion, performance and emission characteristics. This may also introduce a potential guideline to improve engine performance and emission characteristics using diesel and its blends. From the review, it can be said that using diesel and its blends in HCCI engines with biodiesel can improve the overall engine performance and emission characteristics in comparison with CI engines.

Keywords: Combustion; diesel; biodiesel; engine performance; HCCI; emission.

INTRODUCTION

Around the world, internal combustion (IC) engines have become very popular for various purposes. But the emissions produced by these engines are not at a satisfactory level. In order to reduce these emission levels, a new mode of combustion is being sought by engine researchers. In this regard, the homogeneous charge compression ignition (HCCI) combustion mode is one potential solution [1, 2]. HCCI combustion can be defined as a process by which a homogeneous mixture of air and fuel is compressed until auto-ignition occurs near the end of the compression stroke. It is noticeably faster than either compression ignition (CI) or spark ignition (SI) combustion [3]. HCCI technology can improve the thermal efficiency and maintain low emissions and can also be implemented by modifying either SI or CI engines. A wide variety of fuels, combinations of fuels and alternative fuels can be used in this technology [4, 5]. Usually a lean air–fuel mixture is used in HCCI engines. It ignites automatically in several locations and is then burned volumetrically without visible flame propagation [6]. Once ignited, combustion occurs very quickly and it is fully controlled by chemical kinetics rather than spark or ignition timing [7]. For this reason, it is very difficult to control the auto-ignition of the mixture and the heat release rate at high load operations, to meet emissions standards and control knocking [8, 9].

The advantages of HCCI technology are as follows: 1) as HCCI engines are fuel-lean, they can operate at diesel-like compression ratios (>15), thus achieving higher efficiencies than conventional SI gasoline engines [10-13]; 2) they can operate on a wide range of fuels [11, 14]; 3) they can produce a cleaner combustion and lower emissions, and especially NO_x levels are almost negligible [15]. On the other hand, HCCI technology has some disadvantages such as high levels of unburned hydrocarbons (UHC) and carbon monoxide (CO) [8, 16, 17], as well as knocking under certain operating conditions [8, 16]. The study of the characteristics of fuel plays a significant role in HCCI engines because the performance of this type of engine strongly depends on them. The choice of fuel also affects the emission levels. Sometimes the blending of two fuels improves the properties of the fuel and can ultimately provide better engine performance and emissions. In terms of emissions, diesel engines produce higher levels of NO_x and particulate matter [18] or soot, which require proper control strategies because of their negative health and environmental effects. This problem can be solved by using HCCI combustion in IC engines. As HCCI operates on lean mixtures, the peak temperatures are much lower than SI and CI. The low peak temperatures reduce the formation of NO_x. However, the low peak temperatures also lead to incomplete burning of fuel, especially near the combustion chamber walls. This leads to high carbon monoxide and hydrocarbon emissions. An oxidizing catalyst can remove the regulated species, because the exhaust is still oxygen-rich. Due to the significance of HCCI technology, which can be a replacement for conventional CI or SI engines, there is a need to report on recent advances of this technology. In this study, peer-reviewed articles from highly rated journals on commonly used fuel (diesel and biodiesel–diesel blend) in HCCI engines have been reviewed. This report focuses on the fuel properties, engine performance and emission characteristics of the abovementioned fuel and compares the data with CI engines. Each of them is discussed in detail in different sections. Finally, different research results are presented in tabular form to allow easy comparison among them.

FUEL PROPERTIES

The proper operation of an engine depends on a number of fuel properties. Viscosity, density, cetane number, heating value, flash point, pour point etc. are the most significant properties of fuel. Engine performance and emission are directly related to these. Before being used as a fuel, it should fulfill the standard limit defined by various standards such as ASTM, EN, ISO, etc. Among these, ASTM is widely used. Fuel whose properties' values lie within the standard limit provides smooth engine performance and emission. In this regard, the study of fuel properties plays an important role when planning to use a liquid as fuel. The blending of two or more fuels has recently become very popular because it improves these fuel properties. In this study, the properties of diesel and biodiesel–diesel blend in a CI engine are discussed. Table 1 presents the fuel properties of the discussed fuel and blend.

Kinematic Viscosity

Kinematic viscosity is the resistance of liquid to flow. It indicates the thickness of the oil and is traditionally measured by noting the time it takes oil to travel through the orifice of a capillary of a particular size under the force of gravity. It should be lower for better performance of engines because higher viscosity requires the consumption of

more fuel pumping power as well as leading to poor spray and atomization [19-21]. It also increases fuel consumption [22]. From Table 1 it can be seen that the biodiesel–diesel blend has a lower kinematic viscosity than diesel. This ultimately reduces the fuel consumption, in addition to which better spray and atomization can be found.

Density

Density is a physical property which is used to calculate the precise volume of the fuel necessary to supply an adequate combustion. Density and viscosity are directly proportional to each other. Higher density increases the energy concentration of fuel [23], and the fuel atomization efficiency is also influenced by its density [20]. But higher density causes higher viscosity, which ultimately gives poor combustion and affects engine performance and emission [24]. Usually, biodiesel is denser than diesel fuel, but when it is blended with diesel it reaches a acceptable level which is good for better engine performance. From Table 1 it is seen that the blend’s density is slightly higher than diesel.

Cetane Number

The cetane number (CN) is a measurement of the combustion quality of the fuel used in a compression ignition engine. Thus it is the approximate equivalent of an octane rating for fuel used in a spark ignition engine. It is a dimensionless descriptor. There is a close relation between ignition delay and CN. A higher CN shortens the ignition delay period. In this regard, a higher CN is expected. From Table 1 it is seen that the CNs of both the fuel and blend are similar. Thus, it does not create any difference in engine combustion characteristics.

Calorific Value

The calorific value of a fuel can be defined as the amount of heat given out by the complete combustion of a unit quantity of that particular fuel. It is an important parameter to determine the suitability of a fuel [25]. Engine combustion characteristics and performance are influenced by the calorific value. It facilitates the heat release during combustion and improves the power output [26-29]. Usually, biodiesel has a lower calorific value than diesel, but when it is blended with diesel it reaches a acceptable level which is good for better engine performance. From Table 1 it is seen that the blend’s density is slightly lower than diesel.

Table 1. Fuel properties of ordinary diesel and biodiesel–diesel blend.

Properties	Kinematic viscosity 40° C (cSt)	Density (kg/m ³)	Cetane number	Calorific value (MJ/kg)	Flash point (°C)	Pour point (°C)	Cloud point (°C)	Ref.
ASTM limit	1.9-6	---	47 minimum	---	130 minimum	---	---	
Diesel	2.5-5.7	816-840	45-55	43-47	50 -98	-6-5	-16-5	[30-32]
Biodiesel-diesel blend (up to 30% biodiesel)	2.77-4.80	835-896	46.9-49.9	35.6- 44.16	75.5-140	-2-6	-3-10	[33-38]

Flash Point

The flash point can be defined as the temperature of fuel at which it will ignite when exposed to a flame or spark. It has an inverse relation with the fuel's volatility. The flash point has great importance because it directly affects the transportation, storage and handling of fuel. A fuel which has a higher flash point provides safer storage and transport [39]. According to Table 1, the biodiesel–diesel blend has a higher flash point than ordinary diesel, which indicates that the blend is a safer fuel.

Pour Point

The pour point can be defined as the lowest temperature of a liquid at which it can flow. When the temperature of a fluid reaches its pour point, it becomes semi-solid and ultimately loses its flow characteristics, which causes major operability problems [40]. Considering this matter, a higher pour point is expected. As per Table 1, the pour point of the blend is slightly higher than diesel, which is good for engine operation.

Cloud Point

The cloud point is a significant property of fuel for low temperature applications. It is defined as the temperature at which dissolved solids are no longer completely soluble, participating as a second phase giving the fluid a cloudy appearance. In this regard a higher cloud point is desirable. According to Table 1, the biodiesel–diesel blend has a higher cloud point than ordinary diesel, which is good for engine performance.

COMBUSTION CHARACTERISTICS

The engine performance and emission characteristics are directly affected by the combustion characteristics of a fuel. The important parameters that indicate the combustion process effectiveness are in-cylinder pressure, ignition delay, combustion duration, heat release and cumulative heat release rate [41, 42]. In-cylinder pressure can be measured directly from the engine and the other combustion parameters can be calculated from the in-cylinder pressure. The heat release rate is estimated from the first law of thermodynamics using the in-cylinder pressure and the geometry of the crank and connecting rod [43]. The other important combustion parameters can be easily estimated from the heat release rate variation over an engine cycle. This paper illustrates the combustion characteristics of ordinary diesel and biodiesel–diesel blend in HCCI engines, as well as comparing the results with conventional CI engines. Articles reviewed here reveal that HCCI engines produce higher cylinder pressure and heat release as well as shorter ignition delay.

Cylinder Pressure

The in-cylinder pressure measurement is considered to be a very valuable source of information during the development and calibration stages of the engine. The in-cylinder pressure signal can provide vital information such as peak pressure, P–V diagram, indicated mean effective pressure, fuel supply effective pressure, heat release rate, combustion duration, ignition delay and so on [44]. Moreover, based on ideal gas and the first law of thermo-dynamics, it can be used in more complex calculations, for

example, in air mass flow estimation, combustion diagnosis and NO_x prediction [45]. An HCCI engine usually produces a higher cylinder pressure which in turn gives higher efficiency. However, too much pressure is a problem because it may damage the engine cylinder. From Table 2 it is seen that using diesel in an HCCI engine gives a higher cylinder pressure than a conventional CI engine. This pressure can be reduced to a moderate level by blending biodiesel with diesel. Table 3 indicates that proper utilization of biodiesel–diesel blend can minimize the cylinder pressure.

Ignition Delay

One of the most important parameters in the combustion phenomenon is the ignition delay. The ignition delay for any fuel can be calculated based on the time elapsed between the start of fuel injection and the start of combustion [46]. Ignition delay strongly depends on the type of fuel used and its concentration in the cylinder charge. The associated changes in the charge temperature during compression, pre-ignition energy release, external heat transfer to the surroundings and the contribution of residual gases appear to be the main factors responsible for controlling the length of the ignition delay of the engine [47]. The physical and chemical properties of the fuels will affect the ignition delay period, and researchers have stressed that chemical properties are much more important than physical properties. The ignition quality of a fuel is usually characterized by its cetane number. A higher cetane number generally means a shorter ignition delay. In this regard, from Table 1 it is seen that diesel has a higher cetane number than its blend. So this shortens the ignition delay period. Tables 2 and 3 show that using diesel in an HCCI engine gives a shorter ignition delay period than in a conventional CI engine, rather than using biodiesel–diesel blend.

Heat Release

In a typical IC engine, combustion occurs via a flame. Hence at any point in time, only a fraction of the total fuel is burning. This results in low heat release rates. In HCCI, however, the entire fuel/air mixture ignites and burns over a much smaller time interval, resulting in high heat release rates. To withstand the higher heat release, the engine has to be structurally stronger. Several strategies have been proposed to lower the rate of combustion. Mixing fuels with different auto-ignition properties can lower the combustion speed [48]. An HCCI engine usually releases more heat, which sometimes poses challenges in controlling the combustion rates and affects safety and the structural integrity of the engine. From Table 2 it is seen that using diesel in an HCCI engine gives a higher heat release than a conventional CI engine. This heat can be reduced to a moderate level by blending biodiesel with diesel. Table 3 indicates that proper utilization of the biodiesel–diesel blend can minimize the heat release.

PERFORMANCE CHARACTERISTICS

Engine performance is the next parameter that indicates whether an engine is widely acceptable or not. Brake power, brake specific fuel consumption (BSFC) and brake thermal efficiency are the performance indicators for engines. Not only fuel properties but also fuel injection pressure and timing, the air–fuel mixture, amount of injected fuel, fuel spray pattern etc. affect engine performance. Usually engine brake power, brake torque and BSFC are tested against load or speed. This paper illustrates the performance

characteristics of ordinary diesel and biodiesel–diesel blend in HCCI engines as well as comparing the result with conventional CI engines. The articles reviewed here reveal that HCCI engines produce lower brake thermal efficiency and that brake specific fuel consumption is higher than in the conventional CI engine.

Break Thermal Efficiency

The brake thermal efficiency (BTE) of an engine is the ratio of brake output power to input power and describes the brake power produced by an engine with respect to the energy supplied by the fuel. It is a significant characteristic to measure the engine performance. It is clear from Table 2 that using diesel in an HCCI engine does not provide a satisfactory brake thermal efficiency. It is always lower than CI engines. This phenomenon can be changed by using a biodiesel–diesel blend, which can provide higher brake thermal efficiency [49].

Brake Specific Fuel Consumption

Brake-specific fuel consumption (BSFC) is the ratio between mass fuel consumption and brake effective power and it is inversely proportional to thermal efficiency for a given fuel. It is a measure of the fuel efficiency of any prime mover that burns fuel and produces rotational, or shaft, power. It is typically used for comparing the efficiency of internal combustion engines with a shaft output. From Table 2 and 3 it is clear that in the case of brake specific fuel consumption HCCI engines always lag behind CI engines.

EMISSION CHARACTERISTICS

Emissions levels have become a major focus in new engine developments nowadays because regulatory bodies, such as those in Europe, the United States and Japan, are imposing stringent vehicle emissions quality standards [50-52]. Emissions in HCCI engines consist of UHC, CO, NO_x, and smoke. HCCI engines are claimed to have low emissions levels of NO_x and smoke and high levels of unburned hydrocarbons (HC) and carbon monoxide (CO). However, emissions levels vary from one engine to another and are dependent on the operating conditions of the engine, fuel quality and the engine design [53]. Thus, the emissions levels from one engine cannot be directly compared with another engine. This paper illustrates the emission characteristics of ordinary diesel and biodiesel–diesel blend in HCCI engines as well as comparing the results with conventional CI engines. The articles reviewed here reveal that HCCI engines produce very much lower NO_x and smoke as well as higher HC and CO.

NO_x Emission

Since HCCI engines typically operate fuel-lean, the final flame temperature is usually well below 2000 K. At this low post-combustion temperature, chemical reactions that produce oxides of nitrogen (NO_x) are essentially inactive. NO_x is generally formed in a high temperature reaction, where the nitrogen in air dissociates into nitrogen radicals to form NO when reacting with oxygen. Some NO is converted to NO₂ when further reactions occur in the chamber. The HCCI engine has been proven successfully as a low NO_x producing engine. Its NO_x producing rate is very much lower than conventional

CI engines. Tables 2 and 3 show that in almost every case NO_x production is lower than in diesel engines.

Table 2. Different experimental engine performance and emission results using ordinary diesel in HCCI engine compared to CI engine.

Engine	Test condition	Performance	Emission	Reference
1-cylinder, 4S, AC, CI, DI, CR: 17.5:1, RP: 4.4 kW, RS: 1500 rpm	Constant speed, different loads and different percentages of EGR (0% and 10%)	↓: Ignition delay, BTE	↓: NO _x , Smoke ↑: HC, CO	[54]
2-cylinder, 4S, AC, CI, DI, CR: 16.5:1, RP: 4.85 kW, RS: 1500 rpm	Constant speed, different loads and different percentages of EGR (0%, 10% and 20%)	↓: Combustion ↑: Heat release, combustion duration	↓: NO _x	[55]
1-cylinder, 4S, AC, CI, DI, CR: 17.5:1, RP: 4.4 kW, RS: 1500 rpm	Constant speed, different loads and different percentages of EGR (0%, 10%, 20% and 30%)	↓: BTE, combustion, peak pressure	↓: NO _x , Smoke ↑: HC, CO	[56]
1-cylinder, 4S, NA, CI, DI, CR: 18.5:1, RS: 1800 rpm	Constant speed and different loads	↓: ITE ↑: IMEP, cylinder pressure, heat release	↓: NO _x , ↑: UHC, CO —: Soot	[57]
1-cylinder, 4S, CI, DI, CR: 15:1, RS: 1500 rpm	Constant speed and different loads	↓: IMEP	↓: NO _x , HC	[58]
1-cylinder, 4S, WC, NA, CI, CR: 14.8:1	Variable speed and different percentages of EGR (0%, 29%, 42% and 50%)	↓: Cylinder pressure ↑: ISFC	↓: NO _x , Smoke ↑: HC, CO	[59]
1-cylinder, 4S, CI, CR: 19:1, RP: 11 kW, RS: 3000 rpm	Variable speed and different loads	↑: BSFC	↓: NO _x , Smoke ↑: HC, CO	[60]

4S=four-stroke, WC=water-cooled, AC=air-cooled, NA=naturally aspirated, CI=compression ignition, DI=direct injection, CR=compression ratio, RP=rated power, RS= rated speed, ↑: increase, ↓: decrease, —: no change.

HC Emission

Hydrocarbons (HC) in the exhaust exist for one of two reasons: either from fuel that avoids combustion or from intermediate species of hydrocarbons that are formed during combustion and not completely combusted. The formation of hydrocarbons is typically due to local flame extinction, either by misfire or gaps in the cylinder geometry [15]. Since HCCI engines are lean (excess amounts of oxygen), hydrocarbons generally burn to completion except during misfire (or partial burn) conditions at later combustion timings. The HC present in the exhaust of HCCI engines usually comes from the

crevices inside the cylinder, especially the area created near the walls by the piston rings. HCCI engines usually produce a higher rate of HC than conventional CI engines. From Table 2 it is seen that using diesel in an HCCI engine gives always higher HC. This enormous rate of HC can be reduced to some extent by blending diesel with biodiesel. Table 3 shows that in some cases the HC production rate is less than in CI engines.

Table 3. Different experimental engine performance and emission results using biodiesel–diesel blend in HCCI engine compared to CI engine

Engine	Test condition	Biodiesel (%)	Reference fuel	Performance	Emission	Reference
2-cylinder, 4S, AC, CI, DI, CR: 16.5:1, RP: 5.85 kW, RS: 1500 rpm	Constant speed, different loads and different percentages of EGR (0%, 15% and 30%)	20 40	Diesel	↓: ITE, ISFC, heat release ↑: Cylinder pressure	↓: NO _x ↑: HC, CO, Smoke	[61]
1-cylinder, 4S, NA, CI, DI, CR: 18.4:1	Constant speed, different loads and different percentages of EGR (0%, 11.5%, 16.6% and 24.3%)	30 65	Diesel	↓: Cylinder pressure ↑: Heat release	↓: Smoke ↑: HC, CO, NO _x	[62]
1-cylinder, 4S, CI, DI, CR: 17.5:1 RS: 1500 rpm	Constant speed and fixed load	-----	Diesel	—: Cylinder pressure, heat release	↓: NO _x , HC, PM, soot ↑: CO	[63]
4-cylinder, 4S, CI, IDI, CR: 16.5:1	Constant speed and different loads	-----	Diesel	↑: B SFC, BTE	↓: NO _x , HC ↑: CO	[49]
1-cylinder, 4S, CI, DI, CR: 17.5:1 RP: 4.4 kW RS: 1500 rpm	Constant speed, different loads and different percentages of EGR (0%, 10%, 20% and 30%)	-----	Diesel	↓: Heat release ↑: Cylinder pressure	↓: NO _x , Smoke ↑: HC, CO	[64]
1-cylinder, 4S, CI, DI, CR: 16:1	Variable speed and different loads	-----	Diesel	↓: Heat release ↑: Ignition delay	-----	[65]

CO Emission

CO is mainly produced due to incomplete combustion of the fuel. Incomplete combustion occurs when the flame temperature cools down and progression to CO₂ remains incomplete. When the flame front approaches a relatively cool cylinder liner and in crevice volume, the combustion process is slowed down and the flame front is extinguished. If the air–fuel mixture is too rich the amount of oxygen becomes insufficient for complete combustion. HCCI engines usually produce a higher rate of CO than conventional CI engines. From Table 2 it is seen that using diesel in HCCI engines always produces higher CO. This enormous rate of CO can be reduced to some extent by blending diesel with biodiesel. Table 3 shows that in some cases the CO production rate is less than CI engines.

Particulate Matter

Particulate matter [18] emissions differ from unburned hydrocarbons as they are large agglomerations of smaller HC molecules formed in the combustion process. PM manifests itself as “soot” or “smoke” and is common in diesel engines. The formation of PM occurs in fuel-rich zones, whereas the oxidation of these particles occurs in the fuel-lean regions. Characterization generally consists of two different categories, PM10 and PM2.5, where the numeral indicates the maximum diameter of the PM molecule. Therefore, PM10 includes all particles consisting of a diameter less than 10 micrometers. Measurement of PM is done by taking advantage of different collection mechanisms including filtering, interception, impaction, and diffusion. In HCCI engines, the lean operation leads to negligible amounts of PM. Most of the literature reviewed in this paper showed a decreased amount of smoke and soot emission in HCCI engines.

CONCLUSIONS

There is enormous potential for HCCI in the energy sector, as engine producers cannot ignore the emissions and efficiency benefits. The ability to adapt to the alternative (non-petroleum) fuel movement will also have a significant impact on the combustion engines of the future. It can be clearly seen that the HCCI engine has low emissions levels of NO_x, soot and particulates. However, HCCI engines still have unresolved issues which are the high levels of unburned HC and CO emissions. As long as the current energy consumption trends continue and environmental sustainability remains a priority, the energy sector will experience major changes in the near-to-intermediate future. HCCI will most likely play a major role in this revolution, with the extent being defined by our success in addressing the issues highlighted above.

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