INFLUENCE OF INJECTION TIMING ON HCCI ENGINE OPERATED WITH RENEWABLE FUELS

Vijaykumar Totad[1], V. S. Yaliwal[2], N. R. Banapurmath[3], Suneelkumar N. Kulkarni[4], Praveen Harari[5*]

[1,2]Department of Mechanical Engineering, SDM College of Engineering and Technology, Dharwad, Karnataka, India
[3]School of Mechanical Engineering, KLE Technological University, BVB Campus, Hubballi, Karnataka, India
[4]Department of Mechanical Engineering, Cambridge Institute of Technology, Bengaluru, Karnataka, India
[5]Department of Mechanical Engineering, School of Engineering and Technology, CMR University, Bangalore, Karnataka, India

[*]Corresponding Author: Praveen Harari

ABSTRACT

Homogeneous charge compression ignition (HCCI) engines offer high thermal efficiency and ultra-low emissions, but their performance is highly sensitive to fuel properties and injection timing. This study investigates the influence of injection timing on the combustion, performance, and emission characteristics of an HCCI engine fueled with renewable alternatives, including biodiesel, bioethanol, and biogasoline blends. Experiments were conducted across a range of injection timings to evaluate their effects on ignition delay, heat-release patterns, in-cylinder pressure, brake thermal efficiency, and emissions such as NOx, CO, HC, and particulate matter. Results indicate that advancing injection timing enhances mixture homogenization and stabilizes early combustion, yielding improved thermal efficiency but potentially elevating peak pressures. Retarding injection timing delays the start of combustion, reducing NOx formation but increasing unburned HC and CO due to incomplete oxidation. Renewable fuels, with their higher oxygen content and distinct physical properties, showed improved combustion stability and reduced soot formation across all timings, though optimal performance was achieved at moderately advanced injection settings. Overall, the study highlights that careful optimization of injection timing is essential for maximizing the benefits of renewable fuels in HCCI engines, enabling cleaner and more efficient operation while addressing combustion phasing challenges.

KEYWORDS: HCCI engine, Mahua biodiesel, Jamun biodiesel, Injection timing.

NOMENCLATURE

HCCI - Homogeneous charge compression ignition, BTE - Brake thermal efficiency, HC - Hydrocarbon, CO - Carbon monoxide, NOx - Oxides of nitrogen, CNG - Compressed natural gas, JAMNSOB - Jamun seed biodiesel, MAHUAOB - Mahua seed biodiesel, IT - Injection timing, BDF - Biodiesel fuel, CRDI - Common rail direct injection.

1. INTRODUCTION

The automobile industry has relied heavily on fossil fuels since the invention of the internal combustion engine, resulting in an imbalance between fossil fuel production and consumption. Additionally, these internal combustion engines emit several chemicals that are harmful to the environment, and gasoline engines generate more energy with fewer pollutants than alternative fuels [1,2]. The best solution to this problem is a hybrid power system that combines the advantages of an internal combustion engine with the advantages of an electric vehicle. Hybrid vehicles are being developed to increase power, reduce emissions, and improve fuel efficiency. Although hybrid electric vehicles can significantly reduce environmental pollution, they still use traditional internal combustion engines [3,4]. Electrification and hybridization should remove many barriers to public transport use. By introducing advanced combustion principles such as low-temperature combustion, hybrid electric vehicles become cleaner and more efficient. This is a more modern engine method that reduces soot and nitrogen oxide emissions and improves thermal efficiency [5,6]. Advanced fuel injection, variable valve timing, and exhaust gas recirculation technology are now used to achieve this style of combustion. Although low-temperature combustion is the best solution to current vehicle emissions problems, it also has certain limitations. When used in conventional power transmission, the main obstacle is the narrow operating range. Adding an electric motor to the transmission solves this problem and increases the operating range of the motor [7,8]. Hybrid electric vehicles can help in this case, as they combine an electric motor transmission system with a low-temperature internal combustion engine, increasing the power range and enabling higher speeds. There are other low-temperature combustion modes, but two of them are the main focus of this study. Compression ignition with controlled reactivity and direct injection of a uniform charge. In a direct injection homogeneous fuel unit, combustion is initiated by directly injected diesel fuel after the fuel and oxidizer are thoroughly mixed and compressed. One of the two fuels used in a reactivity-controlled compression ignition system is highly reactive and the other is not. Although low reactivity gasoline is compressed, self-ignition does not occur. Towards the end of the compression stroke, highly reactive fuel is injected and the mixture is fully ignited [9-11].

2. FUELS USED FOR THE STUDY

The fuels used in the study are discussed in this chapter. These fuels are compatible to diesel engine as they exhibit desirable physico-chemical properties such as good combustion quality, good oxidation, thermal stability and higher energy density. In the present work, biodiesels of Jamun seed oil and mahua seed oils called JAMNSOB and MAHUAOB and their B20 blends (JAMNSOB B20 and MAHUAOB B20) respectively were used as pilot fuels. Further gaseous fuels of CNG is used as primary injected fuel in the inlet manifold. It has been determined how the aforementioned fuel mixtures affect the HCCI engine's performance, emissions and combustion.

Table-1. Properties of Diesel, JAMNSOB B20 and MAHUAOB B20

Properties	Diesel	JAMNSOB B20	MAHUAOB B20
Density (kg/m^3)	830	862	840
Calorific value (kJ/kg)	43,000	39,718	38,206
Flashpoint (°C)	54	114	128
Kinematic Viscosity (cSt)	2.3	4.58	4.32

3. EXPERIMENTAL SET UP

The current one-cylinder, four-stroke, water-cooled, direct injection, compression ignition conventional engine with a 5.2 kW capacity at 1500 rpm serves as the foundation for the CRDI engine test rig. Figure-1 shows the complete HCCI engine test rig with necessary accessories. Engine specifications are provided in Table-2.

Figure-1. HCCI engine test rig

Table-2. Engine specifications

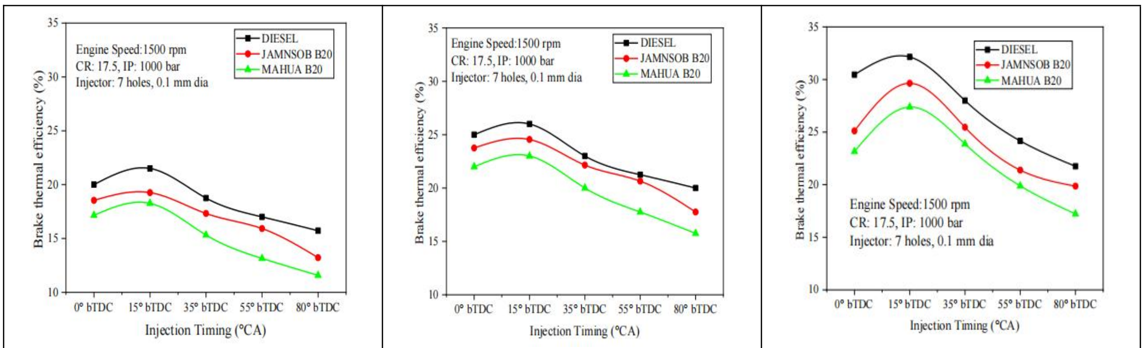
Product	Diesel engine (Computerized)
Engine	Make Kirloskar, 1-cylinder, 4-stroke diesel model
Compression ratio	17.5 : 1
Stroke and bore	110 mm and 87.5 mm
Dynamometer	Eddy current
Cooling	Water cooled
Rated Power	5.2 kW (7 HP) @1500 rpm
Fuel tank Capacity	15 liters with glass fuel metering column

4. RESULTS AND DISCUSSIONS

Experimental tests done on HCCI with in-cylinder CRDI injection of diesel, biodiesels of Jamun seed oil (JAMNSOB B20) and mahua oil (MAHUAOB B20) along with manifold low pressure injection of hydrogen respectively. The performance and emission characteristics of HCCI engine are determined for loads 40%, 60% and 80% respectively. Using an internally developed CRDI which provides fuel with aid of an ECU at the necessary more pressures, biodiesel was injected while CNG was inducted into cylinder.

4.1 Brake thermal efficiency (BTE)

Figure-2 illustrates how the IT affects the HCCI engine's BTE at 40%, 60% and 80% engine loads. As the engine's load grows the BTE rises because more pilot fuel is fed into the engine cylinder. Lower BTE with biodiesel blended fuels is obtained compared with diesel operation. A reduction in BTE was observed with the advancement of fuel IT. Across all load conditions, the minimum BTE occurred at an IT of 80° bTDC. Advancing the IT, delay period increases due to heightened fuel supply to engine cylinder. Further advancing the IT increases the wall wetting associated with lower engine BTE. Wall wetting of fuel on combustion chamber wall when piston moves was away from TDC. Compared to diesel, biodiesel blends functioned HCCI engine performs inferior owed to higher viscosity. Among the biodiesel blends, JAMNSOB B20 outperforms MAHUA B20, primarily due to differences in their fuel properties, which significantly influence engine performance. At an injection timing of 55° bTDC in HCCI mode under 60% load, BTE of 21.25%, 20.65%, and 17.75% were recorded for Diesel, JAMNSOB B20, and MAHUA B20, respectively. In comparison, at 80% load, the BTEs were reduced to 20%, 17.55%, and 15.75%. Overall, the conventional CRDI engine operating on diesel and biodiesel blends exhibited higher BTE values than those observed under HCCI mode.



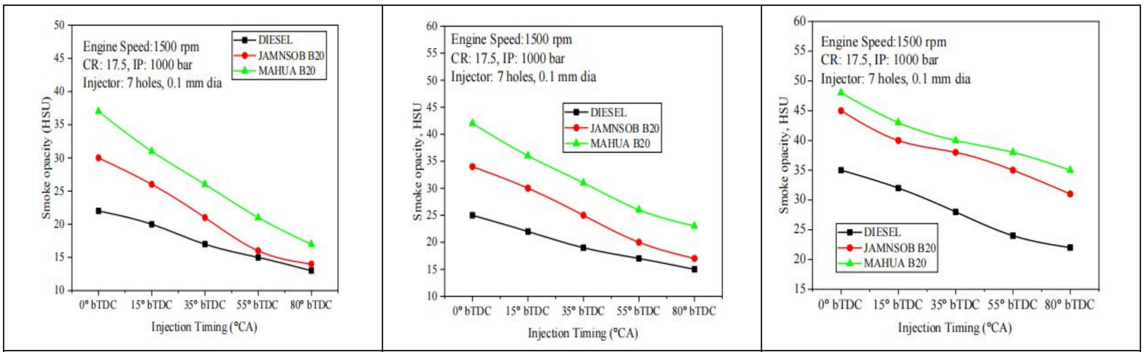
40% Load	60% Load	80% Load

Figure-2. Variation of BTE with ITs of HCCI engine at various loads

4.2 Smoke emissions

Figure-3 presents the smoke emissions from the HCCI engine at load levels of 40%, 60% and 80%. An increase in smoke intensity is observed with rising engine load, attributed to the higher fuel-air ratio. This trend is more pronounced in biodiesel blend operations compared to conventional diesel, likely due to the inherent oxygen content and combustion characteristics of biodiesel. The development of a homogeneous air-fuel combination, which ensures better combustion. For all loads lower smoke with advancing IT of 80° bTDC. The HCCI with B20 displays upper smoke due to viscosity and reduced combustion issues. However, JAMNSOB B20 shows comparatively lower smoke emissions than MAHUA B20. Diesel being common properties of respective biodiesels makes difference in the smoke emissions. Smoke of 17, 20 and 26 HSU is achieved with Diesel, JAMNSOB B20 and MAHUA B20 biodiesel blends at an IT of 55° bTDC in HCCI for 60% load respectively as against 24, 35 and 38

HSU respectively at 80% load. Smoke emissions were larger from conventional CRDI engines running on biodiesel blends.

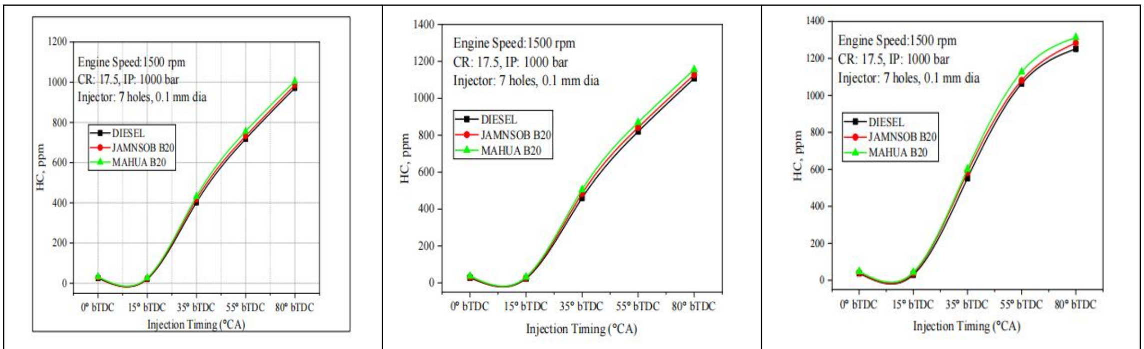


40% Load	60% Load	80% Load

Figure-3. Variation of smoke emissions with ITs of HCCI engine at various loads

4.3 HC and CO emissions

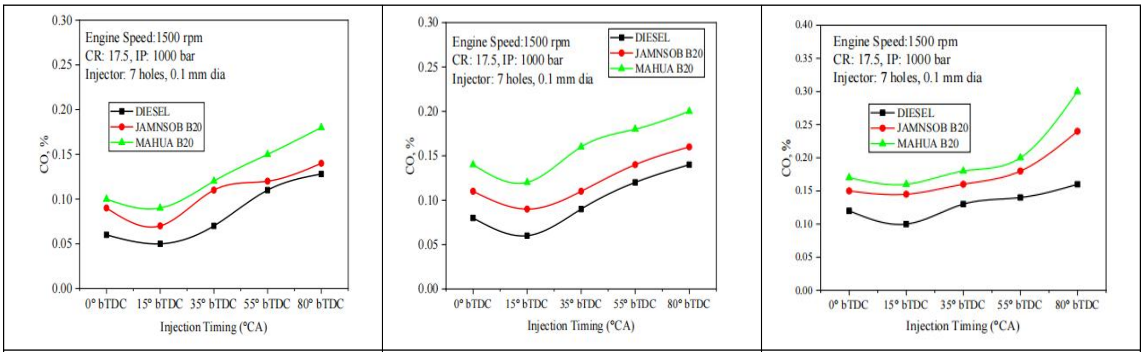
Figures 4 and 5 illustrate how IT affects HC and CO emissions of HCCI engines at operating loads of 40%, 60% and 80%. Due to a larger fuel-to-air ratio, which occurs when more pilot fuel is injected at medium and higher engine operating loads, HC and CO emissions in HCCI engines rise as engine load increases. Biodiesel blended results into higher HC and CO emissions related to diesel operation. HC and CO emissions obtained are of very higher magnitudes observed at 80° bTDC. With a 7-hole injector, heightened wall wetting is seen when the spray strikes the cylinder wall and piston when the piston is distant from TDC, resulting in elevated HC and CO. HCCI results into crank case dilution and is more pronounced at advanced ITs. Higher density and viscosity, BDF blends exhibited higher HC and CO emissions when compared to diesel. JAMNSOB B20 shows comparatively lower HC and CO emissions compared to MAHUA B20. Biodiesels makes the difference in smoke emissions.



40% Load	60% Load	80% Load

Figure-4. Variation of HC emissions with ITs of HCCI engine at various loads

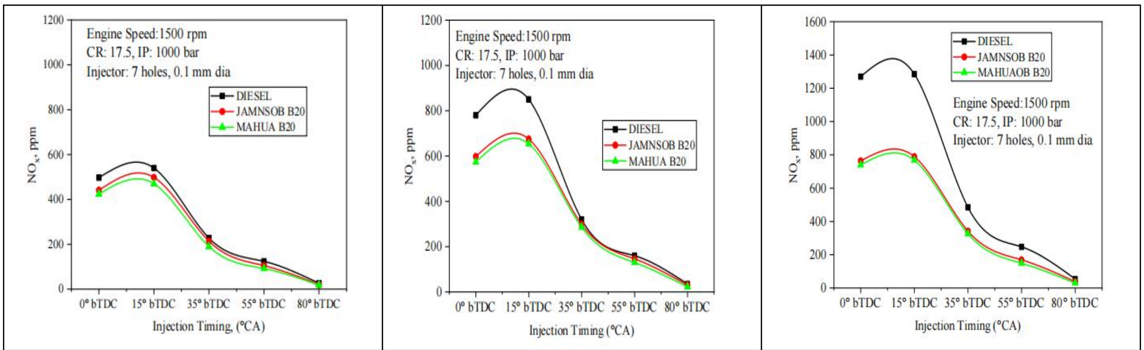
HC emissions of 820, 842 and 870 ppm are attained with Diesel, JAMNSOB B20 and MAHUA B20 biodiesel blends at an IT of 55° bTDC in HCCI for 60% load respectively as against 1064, 1081 and 1127 ppm at 80% load. HC of conventional CRDI engine powered with biodiesel blends showed lower magnitudes compared to HCCI modes of operation. CO emissions of 0.12%, 0.14% and 0.18% are achieved with Diesel, JAMNSOB B20 and MAHUA B20 biodiesel blends at an IT of 55° bTDC in HCCI mode for 60% load respectively as against 0.14%, 0.18% and 0.2% respectively at 80% load. CO emissions of conventional CRDI engine powered with both fuels blends showed lower magnitudes compared to HCCI.



40% Load	60% Load	80% Load

Figure-5. Variation of CO emissions with ITs of HCCI engine at various loads

Figure-6 illustrates how IT affects the HCCI engine's NOx at 40, 60 and 80% engine loads. In comparison to CRDI mode, less NOx emissions attained at IT of 80° bTDC, and fuels displayed a declining NOx with IT. Minor HRR and in-cylinder gas temperatures that are present in combustion chamber may be the cause of the trend that has been noticed. Furthermore, combustion is delayed at higher IT because of an increased ignition delay. Biodiesel blends exhibited slightly lower NOx emissions compared to conventional diesel. At an injection timing of 55° bTDC in HCCI mode under 60% load, NOx emissions were recorded as 160 ppm for diesel, 146 ppm for JAMNSOB B20, and 130 ppm for MAHUA B20. Under 80% load, these values increased to 247 ppm, 169 ppm and 149 ppm, respectively. In comparison, the conventional CRDI engine operating with diesel and biodiesel blends produced significantly higher NOx emissions, attributed to greater in-cylinder pressures and heat release rates characteristic of CRDI combustion.



40% Load	60% Load	80% Load

Figure-6. Variation of NOx emissions with ITs of HCCI engine at various loads

5. CONCLUSIONS

- At an injection timing of 55° bTDC in HCCI mode under 60% load, BTE of 21.25%, 20.65%, and 17.75% were recorded for Diesel, JAMNSOB B20, and MAHUA B20, respectively. In comparison, at 80% load, the BTEs were reduced to 20%, 17.55%, and 15.75%.
- Smoke of 17, 20 and 26 HSU is achieved with Diesel, JAMNSOB B20 and MAHUA B20 biodiesel blends at an IT of 55° bTDC in HCCI for 60% load respectively as against 24, 35 and 38 HSU respectively at 80% load.
- HC emissions of 820, 842 and 870 ppm are attained with Diesel, JAMNSOB B20 and MAHUA B20 biodiesel blends at an IT of 55° bTDC in HCCI for 60% load respectively as against 1064, 1081 and 1127 ppm at 80% load. HC of conventional CRDI engine powered with biodiesel blends showed lower magnitudes compared to HCCI modes of operation. CO emissions of 0.12%, 0.14% and 0.18% are achieved with Diesel, JAMNSOB B20 and MAHUA B20 biodiesel blends at an IT of 55° bTDC in HCCI mode for 60% load respectively as against 0.14%, 0.18% and 0.2% respectively at 80% load.
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