PERFORMANCE AND EMISSION CHARACTERISTICS OF VARIOUS COMBUSTION MODES

Abstract

Concern about diesel engine emission and growing global need for energy in case of transportation sector have made biofuels for IC engines more significant. Huge number of researchers have looked into biofuels in case of dual fuel engines in order to optimize emission profiles and energy consumption for transportation and distribution activities. This review article comprehensively compares the engine performance, combustion, and emission characteristics of alternative fuels in conventional, dual fuel, and RCCI mode combustion. The RCCI engine had favourable emission characteristics due to differences in fuel qualities, spray droplet size distribution, and subsequent mixing with ambient air. The RCCI technique is capable of controlling the combustion phase, peak pressure rise and heat release rate through regulating the reactivity stratification to attain the resolution of combustion process optimization.

Keywords: Conventional, Dual fuel, RCCI, Performance, Emission.

Author

Dr. Praveen Harari
Department of Mechanical Engineering
School of Engineering and Technology
CMR University
Bengaluru, Karnataka, India.

Nomenclature: BTE: Brake thermal efficiency, HC: Hydrocarbon, CO: Carbon monoxide, NOx: Oxides of nitrogen, PM: Particulate matter, RCCI: Reactivity controlled compression ignition, HCCI: Homogeneous charge compression ignition, EGR: Exhaust gas recirculation, aTDC: After top dead center, bTDC: Before top dead center, CNG: Compressed natural gas: CBG: Compressed biogas, HSU: Hartridge smoke unit, IC: Internal combustion

I. INTRODUCTION

Population expansion is increasing energy demand in the transportation sector, while economic policies strive to increase efficiency and decrease dangerous emissions such as NOx, HC and PM. Clean, high efficiency engines are required to meet the strict emissions rules and deliver power effectively. The effectiveness of modern engines has been increased by the investigation of numerous approaches. Increased mixing of air and fuel will boost combustion performance while lowering PM emissions. The development of dual fuel combustion techniques can also make use of more sophisticated fuel injection systems. Both compression ignition and spark ignition engines have shown to benefit from dual fuel combustion techniques [1-17]. Dual fuel injection systems have lately been employed to promote the use of less reactive fuels and to enable more advanced combustion strategies. Some dual fuel combustion modes have showed substantial promise in terms of efficiency and pollution emission. This is frequently accomplished throughout a large operating range by using two fuels with different concentrations at the same time to induce premixing of the fuel or stratification of the reactivity of the in-cylinder mixture. Dual fuel injection techniques have historically been employed on compression ignition engines to convert old diesel engines to run on less expensive fuel. The implementation allowed for lower PM emissions in addition to the use of a different power source. Although dual fuel engines have the potential to be extremely efficient and environmentally friendly, their use may also be constrained by infrastructure issues and customer acceptance. Users will need to fill up two fuel tanks, and they must have access to the necessary fuels over a sufficiently large area [18-30]. The RCCI technique is capable of controlling the combustion phase, peak pressure rise and heat release rate through regulating the reactivity stratification to attain the resolution of combustion process optimization, stimulating thermal efficiency and decreasing engine-out emissions.

RCCI mode of combustion is emerged from dual fuel combustion in which two fuels of variant reactivity are used to increase the process of combustion and diminish the engine-out emissions. RCCI combustion characteristics are controlled by changing the fuel quantity of the charge. Low reactive fuel is most important key factor that affects the performance and combustion characteristics of RCCI engine. It is not only affects the mixing of fuel and air inside the combustion chamber, but also affects the processes of heat transfer and heat release. At initial stage of RCCI combustion study, gasoline is used as the low reactive fuel and it could achieve lower emissions of NOx and soot along with higher indicated mean effective pressure. In latest years, alcoholic fuels are used as the low reactive fuels for RCCI combustion mode and gained huge attention from various researchers due to their outstanding physico-chemical properties [31-39].

II. EXHAUSTIVE REVIEW ON CONVENTIONAL, DUAL FUEL AND RCCI COMBUSTION MODES

1. Conventional Mode of Combustion:

- **BTE:** At 80% load, the maximum BTE values for diesel and methyl ester of rice bran oil were determined to be 31.09% and 28.27%, respectively [3]. Injection timing of 26° bTDC was shown to be more thermally efficient for 3-hole nozzles than injection timings of 23 and 20° bTDC [4,11,15]. The BTE increased with increasing load for all of the fuels examined. At all power outputs, the BTE of biodiesel blends was found to be lower than that of diesel. At 80% load, all evaluated fuels had higher BTE than at 100% load [5-8, 16]. Among the many nozzles examined, the 5-hole nozzle provided the highest BTE [9]. The karanja B20 blend's BTE was 25.52%, which was higher than that of other biodiesel mixtures [10]. For diesel, simarouba oil methyl ester, and hippe oil methyl ester biodiesels, the BTE amplified with load. At full load, hippe oil methyl ester B20 outperformed simarouba oil methyl ester B20 in terms of BTE [12]. Among the injection pressures examined, 230 bar provided the highest BTE, followed by 210 and 250 bar. Thermal efficiency decreased at 250 bar when compared to 230 bar [13]. Among the biodiesels tested, diesel had the highest efficiency, with 2.79%, 5.89%, 7.75%, 9.64%, and 14.03% higher than B10, B20, B30, B40, and B100 karanja biodiesel blends [17]. Ceiba pentandra oil methyl ester B20 demonstrated higher BTE than nigella sativa oil methyl ester B20 due to its higher calorific value and lower viscosity [25]. Because of their lower calorific value and higher viscosity, higher biodiesel blends have lower BTE than diesel [40-52].

- **Smoke Emissions:** Rice bran oil methyl ester produced more smoke than diesel. At 100% load, the smoke level was 72 HSU for diesel and 80 HSU for rice bran oil methyl ester [3]. For diesel, jatropha oil methyl ester, and their mixtures, the smoke opacity rose as the brake power increased. The smoke opacity rose as the proportion of jatropha oil methyl ester in the diesel blend increased. At 80%, the smoke level was 67 HSU for the methyl ester, 63 HSU for the B20 blend, and 84 HSU for the B80 mix. At 80% load, the smoke level with diesel was 63 HSU [7]. Because of the B0 fuel blend mixed better with the air, it emitted less smoke than the other blends tested. Among the several injection timings evaluated, 26° bTDC produced the least amount of smoke [11]. Among the various injection pressures evaluated, 230 bar produces less smoke than 210 and 250 bar [13,15]. The viscosity of the blends grew as the percentage of biodiesel in the blends increased, resulted in greater smoke. Among the biodiesels tested, diesel had the lowest smoke emissions, which were 6.06%, 12.9%, 20.68%, 29.62%, and 39.88% lower than B10, B20, B30, B40, and B100 fuel blends [17]. Due to better fuel characteristics, ceiba pentandra oil methyl ester B20 emitted lower exhaust emissions than nigella sativa oil methyl ester B20 [25].

- **CO and HC Emissions:** Rice bran oil methyl ester produced more CO and HC than diesel. For diesel and rice bran oil methyl ester, the HC emissions were 60 ppm and 71 ppm at full load. CO levels at full load for diesel and rice bran oil methyl ester were 0.2% and 0.51%, respectively [3]. The HC emissions from B20, jatropha oil methyl ester, and diesel were found to be 66 ppm, 70 ppm, and 40.5 ppm. The CO emissions from B20, jatropha oil methyl ester, and diesel were 0.1245%, 0.132%, and

0.1125% [7]. When compared to biodiesel blends, plain diesel emitted less CO and HC emissions [8]. Among the numerous nozzles evaluated, the 5-hole nozzle emits the least amount of CO and HC emissions. The CO and HC emissions increased with the 4-hole nozzle [9]. When compared to other biodiesel blends, the karanja B20 fuel blend emitted 63 ppm less HC emissions. When compared to biodiesel blends, the karanja B20 blend emitted 0.26% less CO emissions [10]. Among the different injection timings examined, 26° bTDC has the lowest CO and HC emissions because there was more time available for fuel and air mixing as the injection timing advanced from 20 to 26° bTDC [11]. Because of nanoparticles supply oxygen for the oxidation of HC during combustion, the addition of aluminum oxide nanoparticles reduced HC emissions [12]. Among the various blends evaluated, the B100 blend emitted more HC emissions than the other gasoline mixtures [13,16]. Among the various injection pressures studied, 230 bar emitted less HC than 210 bar and 250 bar [13]. The CO and HC emissions from incomplete combustion were more visible in karanja biodiesel and its mixtures B30 and B40 than in diesel. In comparison to the other B30 and B40 blends tested, B20 yielded acceptable levels of CO and HC [17]. Due to differences in fuel characteristics, ceiba pentandra oil methyl ester B20 emitted less CO and HC than nigella sativa oil methyl ester B20 [25].

- **NOx Emissions:** The NOx emission values for rice bran oil methyl ester were 1147 ppm, compared to 1120 ppm for diesel operation at 100% load [3]. For all fuel combinations, NOx emissions increased as load increased. The NOx emissions were 1193 ppm, 1096 ppm, 921 ppm, 903 ppm, and 1100 ppm for B20, B40, B60, B80, and B100, respectively, compared to 900 ppm for diesel running at full load [7]. When compared to biodiesel mixtures, plain diesel emitted a higher level of NOx [8,16]. Among the several nozzles studied, the 5-hole nozzle emitted the most NOx. Because the spray pattern of the 4-hole nozzle was uneven, the greatest amount of fuel impinged on the cylinder wall, NOx emissions were reduced [9]. When compared to biodiesel blends, the karanja B20 blend emitted more NOx (1205 ppm) [10]. Among the several injection timings investigated, 26° bTDC emitted the most NOx [11]. Among the various injection pressures studied, 230 bar emitted more NOx than 210 and 250 bar [12]. B20 produced slightly higher NOx emissions than the other B30 and B40 blends tested [17]. Due to differences in fuel characteristics, ceiba pentandra oil methyl ester B20 produced more NOx than nigella sativa oil methyl ester B20 [25].

2. Dual Fuel Combustion:

- **BTE:** The rate of EGR increased the BTE [18]. Venture carburettor exhibited greater performance over the simple carburettor in terms of BTE. At 80% load, the BTE values for diesel and CNG for 3 mm hole geometry carburettor was 26.16%. The BTE for rice bran biodiesel and CBG operation was 22.88% with the same engine condition [19]. The BTE amplified for 80 and 100% load conditions as the timings of injection were moved from 19 to 27° bTDC [20,21]. The pilot fuel's timings of injection enhanced the BTE of a engine operated with biogas. In comparison to the biodiesel and biogas mode of combustion, the diesel and biogas mode demonstrated higher BTE [22]. More hydrogen gas flow rates reduced the BTE. The BTE of a engine powered by B20 nigella sativa oil biodiesel was greater than that of a B20 jack fruit biodiesel [23]. Increasing the timing of injection for a engine boosted engine performance, and hence BTE increased until 27° bTDC, after which it dropped. Due to differences in fuel characteristics, biogas, a typical diesel fuel powered dual fuel engine, demonstrated increased BTE [24]. When compared to dairy scum biodiesel based dual fuel combustion, induction of producer gas and injection of diesel combustion improved BTE by 12.5% [26].

- **CO and HC Emissions:** The use of 9 mm venture reduced CO and HC emissions. The B100 and B20 blends with CNG had lower amounts of CO and HC than B100 and B20 blends with biogas [27]. In comparison with baseline operation, the engine powered with an emulsion of 20% water in the diesel fuel with the manifold ethanol injection reduced CO and HC emissions by 24.3% and 21% at 80% load condition [28]. Dual fuel engine operating with B20 mixture of jack fruit and nigella sativa with hydrogen induction emits less CO and HC than pure biodiesels [29]. Although the induction of producer gas was the same, the biodiesel operated dual fuel operation produced 32.6% and 29.8% more HC at 80% load than diesel fuel combustion without any nanoparticles. CO levels reduced by 20.6%, 14.8% and 8.2% at 80% load as related with biodiesel powered dual fuel combustion without nanoparticles [30].

- **NOx Emissions:** NOx emissions reduced as the rate of EGR was increased [18]. At 80% load, NOx levels for diesel-compressed biogas and biodiesel-compressed biogas operation with a 3 mm hole geometry carburettor were 943 and 815 ppm, respectively [19]. NOx emissions increased significantly when injection timing increased [20,21]. Advancing injection timing from 19 to 31° bTDC resulted in a 40.02% increase in NOx emissions [22]. The engine powered with B100 fuel blend exhibited greater NOx emissions as related with the B20 fuel blend. As the hydrogen flow rate increased, resulting in higher peak pressure rise and heat release rates within the combustion chamber of dual fuel engine operation, and hence higher NOx emissions [23]. Adding nanoparticles to algae biodiesel increased dual fuel engine performance significantly by increasing peak pressure rise and heat release rates resulted in higher NOx output when compared to algae biodiesel and its blend [24]. Diesel based dual fuel combustion mode raised NOx levels by 26.4% when compared to dairy scum biodiesel based dual fuel operation for same quanity induction of producer gas. Dairy scum biodiesel and producer gas with hydrogen and 5% EGR had 12.4% higher NOx levels than without EGR. When compared to combustion with a 5% EGR rate, higher EGR rates reduced NOx emissions by 32.2% [26].

- **Smoke Emissions:** Ceiba pentandra biodiesel B100 and B20 with purified biogas in dual fuel mode operation produced less smoke than Ceiba pentandra biodiesel B100 and B20 with raw biogas operation. The B20 blend produced less smoke than the B100 blend due to the blending of biodiesel with diesel, which affected and enhanced the fuel property of the B20 blend [22]. With greater hydrogen gas flow rates, there was less smoke emissions. When compared to B20 fuel, the B100 fuel produced more smoke for pilot fuels [23]. As the performance of the dual fuel engine improved, smoke emissions decreased until they reached 27° bTDC, after which they increased again. In dual fuel mode, algae biodiesel B20 emitted less smoke than B100 blend with biogas induction [24]. Diesel based dual fuel operation with producer gas emitted 27.4% less smoke than dairy scum biodiesel based dual fuel combustion.

Dairy scum biodiesel and producer gas with hydrogen and 5% EGR reduced smoke levels by 10.2% when compared to the same fuel combination without EGR [26]. The 9 mm venture had lower smoke opacity than the other ventures examined. Smoke levels were found to be higher in jamune oil biodiesel and biogas injected operation than in CNG powered dual fuel mode operation [27].

3. RCCI Combustion:

- **BTE:** With amplified in the amount of gasoline as the low reactive fuel, BTE decreased [31]. RCCI engine BTE improved against HCCI mode up to 40% gaseous energy share, but declined with further increament in the gaseous energy share [32]. With increasing pentanol content, BTE declined. At 10% injection of pentanol, the diesel and pentanol fuel combination had a better BTE of 22.15%, which was roughly 9.1% and 27.3% greater than other fuel mixtures [33]. The 75% load variation has higher BTE than 50% load variation. At 75% load, a higher BTE of approximately 29.74% was attained for the diesel and CNG fuel combination [34]. The BTE amplified as the timing of injection increased from 45 to 50° aTDC. The BTE reduced as the injection timing increased from 50 to 55° aTDC [35]. The engine's BTE increased as the gaseous energy contribution grew up to 40%, but dropped over 40% [36,38].

  When CNG was used as a low reactive fuel, the engine's BTE improved [36]. The BTE of dropped as the proportion of n-butanol amplified. The highest BTE was found for a diesel and n-butanol mixture containing 10% injection of n-butanol [37].

- **NOx Emissions:** The concentration of NOx decreased as the fraction of gasoline increased [31]. NOx emissions were lowered as the energy percentage of gaseous fuels amplified. When compared to other fuel combination types, diesel and hydrogen produce more NOx emissions [32]. NOx emissions reduced as pentanol fraction increased. At 10% pentanol, the diesel and pentanol fuel combination produced the highest NOx emissions [33]. The 75% load variation produced more NOx than the 50% load variation. The diesel and CNG fuel mix produced higher NOx emissions [34]. Among the various injection timings studied, 50° aTDC emitted more NOx than 45 and 55° aTDC [35]. As the energy share increased, the fuel and mixture become lean, resulted in low-temperature combustion. The low temperature combustion technique reduced NOx emissions [36]. NOx emissions dropped as the proportion of n-butanol amplified. The highest NOx emissions were obtained for a diesel and n-butanol fuel mixture containing 10% injection of n-butanol [37]. When compared to other fuel combinations, RCCI engines operated by diesel and producer gas produced higher NOx emissions [38].

- **Smoke Emissions:** In comparison with other fuel combinations, the pilot diesel and manifold hydrogen fuel combination produced less smoke emissions [32]. Smoke emissions reduced as the quantity of pentanol amplified. The pentanol and diesel had the lowest engine-out smoke emissions when 10% pentanol was used in injected fuels [33]. When compared to the 50% load variation, the 75% load variation emitted less smoke. Among the various fuel combinations, diesel and compressed natural gas emitted less smoke than other fuel combinations [34]. Smoke emissions were quite minimal while using the RCCI combustion mode. Injection timing of 50° aTDC produced less smoke than injection timing of 45 and 55° aTDC [35]. Smoke pollutants dropped as the proportion of n-butanol increased. At 10% n-butanol quantity in manifold injected fuels, the fewer smoke engine-out emissions were recorded for n-butanol and diesel [37]. When compared to other fuel combinations, the RCCI engine driven by diesel and producer gas produced less smoke. Biodiesel activity produced more smoke [38].

- **CO and HC Emissions:** The growth in gasoline percentage increased CO and HC emissions. Biodiesel fuelled engine resulted in higher CO and HC emissions [31]. When compared to other fuel combination types, diesel and hydrogen produce less CO and HC emissions [32]. As the pentanol injection percentage was increased, the CO and HC emissions were also increased. At 10% pentanol in injected fuels, diesel and pentanol produced the lowest CO and HC emissions [33]. In comparison with 50% load condition, the 75% load condition resulted into lower CO and HC emissions. Diesel and CNG produced the least amount of CO and HC emissions of the fuel combinations examined [34]. Among the numerous injection timings investigated, 50° aTDC emitted the fewest CO and HC emissions. Biodiesel-powered RCCI combustion provided a greater quantity of CO and HC emissions [35]. CBG powered engine exhibited higher CO and HC engine-out emissions than CNG as a low reactive fuel [36]. The proportion of n-butanol enhanced the CO and HC emissions. At 10% n-butanol concentration in manifold injected fuels, the lowest CO and HC emissions were recorded for n-butanol and diesel fuelled engine [37]. When compared to other fuel combinations, diesel and producer gas powered RCCI combustion modes produced lower CO and HC emissions [38].

III. CONCLUSION

According to the extensive literature review, RCCI mode is one of the best combustion control that maintains higher thermal efficiency along with lower emissions. The RCCI mode of combustion is more advanced than other low temperature combustion modes. The ignition timing in RCCI combustion can be adjusted by altering the ratio of higher cetane fuel to higher octane fuel. With the addition of high reactive fuel to RCCI combustion, nitric oxide emissions were reduced. The CO and HC emissions from RCCI combustion were somewhat increased. Biodiesel can be used to partially replace diesel, reducing the requirement of diesel and providing an environmentally friendly energy source.

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