

Effect of combustion geometry on combustion, performance and emission characteristics of CI engine using simarouba oil methyl ester

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Abstract. Present study investigates the effect hemispherical (HCC), cylindrical (CCC), toroidal (TCC) and toroidal re-entrant (TrCC) type combustion chamber (CC) geometry on the characteristics of combustion, performance and exhaust emissions from the engine using simarouba oil methyl ester (SuOME) and to compare with base engine operated with diesel fuel. Simarouba oil biodiesel is prepared by 2 stage transesterification using methanol and KOH. 4-stroke naturally aspirated single-cylinder water-cooled direct-injection diesel engine with different optimized injection parameters of injection pressure to 240 bar, injection timing to 27°bTDC, 6 hole injector of 0.2 mm diameter, and loading condition at rated speed of 1500 rpm were used for testing. Ignition delay (ID), combustion duration (CD), peak pressure (PP), brake thermal efficiency (BTE), exhaust gas temperature (EGT) and exhaust emissions (HC, CO, smoke opacity and NO_x) were measured to estimate the behaviour of the diesel engine running on SuOME with different combustion geometry. Results were indicated that, use of SuOME reduces the engine performance with increased emissions compared to fossil diesel conventional fuel. However use of toroidal re-entrant CC gave the better combustion and performance with reduced emission except NO_x comparing with other combustion chamber design.

1. Introduction

In order to warrant the successful combustion and reduced emission from CI engines, a thorough study and optimization of injection parameters like nozzle structure and spray characteristics is crucial since it has control on the fuel atomization, mixing process, evaporation, combustion mechanism and the rate of heat release [1-6]. To meet the stringent forthcoming emission guidelines, along with study of injection characteristics, clean combustion concept together with best alternative for commercially available diesel fuel will play an increasingly significant role [7]. Various studies shown that the deviation in performance and emissions rates based on the injection parameters, combustion chamber shapes and types biodiesel used. Suryawanshi *et al.* [8] reported that by retarding the injection timing



by 4° crank angle slight increment of BTE is obtained at part loads with no changes at full loads using pongamia biodiesel blends. Agarwalet al. [9] observed, a extended spray tip penetration and greater spray region due to the higher injection pressure and after similar elapsed moment beyond the start of injection (SOI) for both diesel and different blends of Karanja methyl ester.

Kuti et al. [10] examined the characteristics of combustion and spray formation of Palm biodiesel using a CRDI system and they have compared with fossil diesel fuel. Due to the higher flash point of biodiesel, longer liquid length is observed inside the combustion chamber. Due to higher cetane number, higher injection pressure and reduced nozzle hole diameter a shorter ignition delay was observed. Mani et al. [11] reported the increment of BTE and CO₂ for all the injection timing operated using a fuel derived from waste plastic oil in a diesel engine. Puhan et al. [12] studied the behavior of fuel and its effects on the engine performance using linseed oil methyl esters with varied injection pressure. Injection pressure of 240 bar was selected as optimized, based on observation that BTE was nearer to that of fossil fuel with reduced CO and slight increment in NO_x emissions. Longmanet al. [13] conducted experiment and concluded that, injection of fuel considerably affects the fuel vaporization; dispersion and distribution and fuel mixing with air within the CC which in turn accountable for the performance and lower emissions of a compression ignition (CI) engine. Yaliwal et al. [14] noticed that improvement in the performance, ignition delay, heat release rate, smooth engine operation and trade-off between smoke and NO_x emissions with 4 hole 0.25mm nozzle geometry along with re-entrant CC. Jakubowski [15] has patented for extensive work carried on multihole nozzle. The study was focused on various methods to increase atomization of the fuel inside the combustion chamber with higher efficiency and purity is exhaust gas. Mahakul et al. [16] has also carried more work on modifiedpiston, better results were obtained in terms of high compression ratio which increases the temperature of combustion chamber and also better air-fuel mixing and low emissions for all modified engines than base engine.Sakthisaravanasenthil et al. [17] carried experimental work on re-entrance combustion geometry and observed 20% and 24%reduction in HC and CO respectively.While soot particles decreases by 19% and NO_xincreases by 12% with omega type combustion chamber geometry incompression of HCC witnessed by Bawankar et al. [18].

Xiangrong et al. [19] Combustion and emission characteristic were investigated by both experimentally analytically, the results shown that for multi swirl combustion chamber, accelerates the fuel/air mixture, enlarges the fuel diffusion space, reduced local fuel rich mixture and decreases the combustion duration with lower fuel consumption and reduced soot emission.Bin Wang et al. [20] carried out analytical investigation to optimize the combustion chamber based on reduction of HC and CO emissions and enhancement in combustion efficiency, reduced emission are obtained because of grater tumble flow, greater squish owing to the greater area of piston top terrain in the squish zone largely enhanced the in-cylinder turbulent kinetic energy by deep bowl piston, compared to the baseline piston. Lalvani et al.[21] conducted experiment using adelfa biodiesel with a blend ratio of 20% using hemispherical and turbulence inducer piston and for various injection pressure, result showed for turbulence inducer piston at 220 bar pressure is higher in terms of break thermal efficiency and break specific energy consumption and lower emission products with higher NO_x emission compared with neat diesel fuel. Mamilla et al.[22] observed 20% of Jatoropha fuel blend with neat dieselalong with toroidal combustion chamber (TCC) gave better efficiency with minimum HC, smoke density and CO₂ emissions, whereas level of NO_x emissions were higher when compared to spherical and re-entrant combustion chamber and other blending ratio's. Jaichandar et al. [23] used pongamia oil methyl ester with different CC shapes and for different injection pressure and concluded that 220 bar is optimum for Toroidal re-entrant CC. At this operating condition BTE was higher and BSFC is lower with reduction in unburnt hydrocarbon, smoke opacity and CO with slight increase in NO_x.Wickman et al.[24]extensive simulation work has done by using KIVA-GA code for Re-entrant piston bowl to find the effect of Swirl ratio, start of injection, EGR, IP, Cr and found reduced in emission levels like CO, CO₂, and also in NO_x with lesser BSFC. Bergstand et al. [25] Esperimental work is done using 6 hole nozzle with different orifice diameter for different engine speeds and observed reduction in soot and other emissions for lower load and 0.09mm orifice diameter.

Effects of CC geometry on the combustion characteristics of fossil fuel along with biodiesel blended fuel operations have been reported. Literature recommend that the effect of nozzle and CC geometry on the performance of simarouba biodiesel fueled engine has been less investigated. Hence, the present work is taken forward to enhance the efficiency and to decrease emission levels. Therefore it is required to find the optimized combustion chamber for engine running under 100% biodiesel to meet the performance of biodiesel near to neat diesel and aiming towards reduction of HC and CO emissions. The purpose of this present study is to explore the combustion and emissions characteristics of both simarouba methyl ester and neat diesel with standard compression ratio for different CCs with optimized fuel injection parameters and nozzle geometry using water cooled single cylinder direct injection CI engine. Important conclusions are finally summarized based on the results obtained.

2. Experimental setup and procedure

2.1. Experimental setup

The schematic of experimental engine test rig setup used for evaluation of performance, combustion and emission characteristics of SuOME at optimized injection parameters, nozzle geometry and different combustion chamber geometry is shown in Fig.1. Detailed specifications of the test engine used for present study are given in Table 1. The speed and torque of the engine is controlled automatically by an eddy current dynamometer. A HAR-TRIDGE smoke meter and DELTA 1600 S Exhaust Gas Analyzer was suitably employed to determine the regulated emission levels such as HC, CO and NO_x which uses non dispersive infrared technology. Gas analyzers were initially calibrated before the start of trial tests. The in-cylinder pressure was obtained by using a piezo-electric type pressure sensor mounted on the head of engine cylinder.

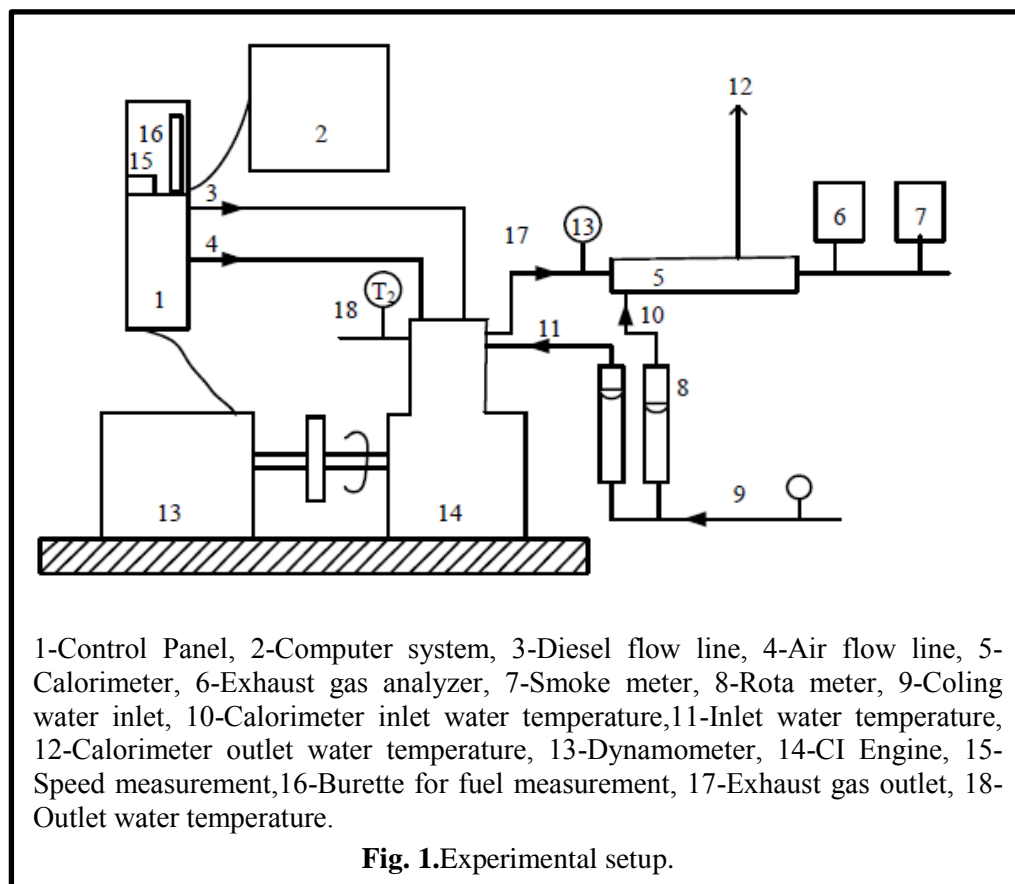
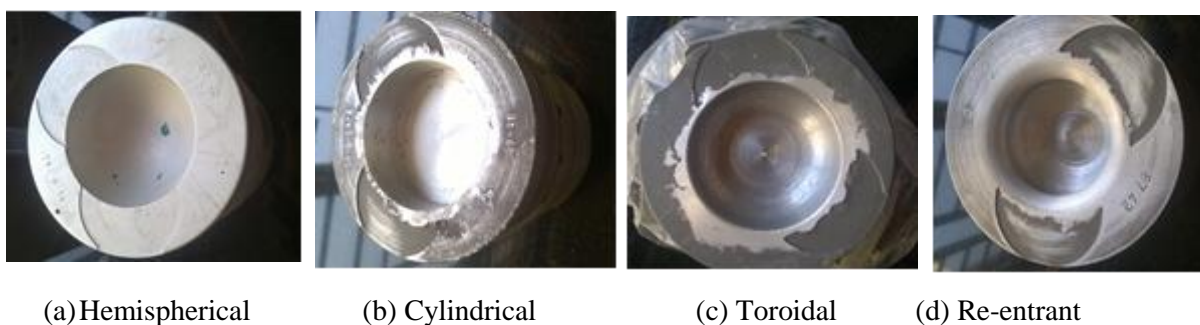


Table 1 Technical specification of the engine test rig.

Sl No	Parameters	Specification
1	Type of engine	Kirloskar make Single cylinder four stroke, direct injection diesel engine
2	Nozzle opening pressure	Range - 205 to 260 bar
3	Rated power	5.2 KW (7 HP)@1500 RPM
4	Cylinder diameter (Bore)	87.5 mm
5	Stroke length	110 mm
6	Compression ratio	17.5:1

2.2. Experimental procedure

Initially, combustion and emission characteristics of test engine were investigated at various injection pressures that is varied from 205 to 260 bar, varied start of injection timings from 19^0 - 31^0 bTDC, different nozzle holes from 3-6 numbers, diameter of nozzle hole at 0.3 mm and 0.2 mm. All the experiments were conducted at engine maximum torque speed of 1500 r/min for different loading conditions starting from zero to full load using diesel as fuel. Based on the results obtained, engine operating values were optimized as follows. Injection timing- 27^0 bTDC, Injector opening pressure – 240 bar, number of holes on injector -6, Diameter of each holes – 0.2 mm. Later, effect of combustion chamber geometry was studied for HCC, CCC, TCC, TrCC shape. Fig.2.shows different combustion chamber shapes (pistons) opted for present study. Using the optimized values and different combustion chamber shapes, experiments were initially carried out with neat diesel as fuel later with using Simarouba methyl ester SuOME as fuel. For each loading conditions test was repeated 3times, the data obtained were averaged to obtain single lined result. Finally, the results like brake thermal efficiency, peak engine pressure, ignition delay, combustion duration and exhaust gas temperature along with emissions like smoke capacity, HC, CO and NO_x were compared with baseline data and analyzed.

**Fig.2.** Combustion chamber shapes

3. Results and discussion

In this section combustion, performance and emission characteristics of single cylinder direct injection diesel engine operated using diesel, SuOME with modified CC shapes namely hemispherical (HCC), cylindrical (CCC), toroidal (TCC) and toroidal re-entrant (TrCC) type for optimized injector pressure and nozzle geometry were presented. The results obtained and detailed analysis on the performance

combustion and emission characteristics of CI engine operating on above mentioned two biodiesels is discussed in the succeeding paragraphs.

4.1 Combustion characteristics

Combustion trend of diesel fuel will diverge when biodiesel is used as fuel in CI engine, and it depends on the viscosity, self-ignition temperature and mixture quality and other properties also. Use of TrCC in a CI engine significantly affects the fuel distribution and mixing of air and fuel in a CC and hence affects the combustion characteristics of fuel. The various combustion characteristics for SuOME fuel operation tested under pre-optimized values of IOP (240 bar), IOT (27° bTDC), number of nozzle hole (6 numbers) and its diameter (0.2 mm) are summarized below.

4.1.1 Ignition delay period

Ignition delay variation with brake power at two loads equivalent to 80% and 100% of the engine full load at the standard operating speed and compression ratio using diesel and SuOME as fuel with four different combustion chamber shapes and its comparative results are plotted in Fig. 3. The ignition delay period depends on the cetane number, specific gravity and viscosity of the fuel and it is determined by knowing the static injection timing. From graph it is noticed that, ignition delay lowers with amplified break power for all CC shapes. This may be caused by improved air fuel mixing, increased amount of fuel burnt inside combustion chamber, subsequently higher combustion temperature, and dilution of exhaust gas at higher loads. However, ignition was 0.4° CA less for diesel fuel compared to SuOME for HCC at full loading condition, this is due to lower cetane number of SuOME than diesel fuel. The delay is shortened by 0.3° CA for TrCC than HCC for SuOME at full load for SuOME.

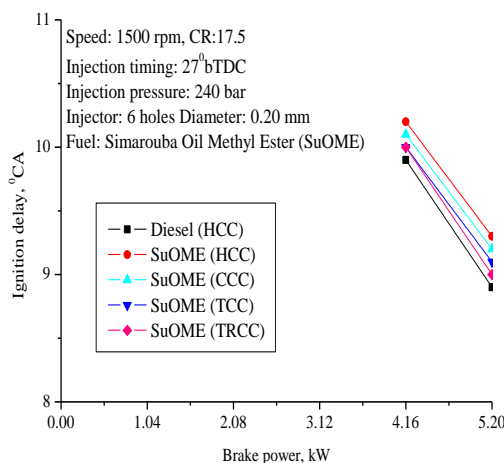


Fig. 3. Variation of ignition delay with BP

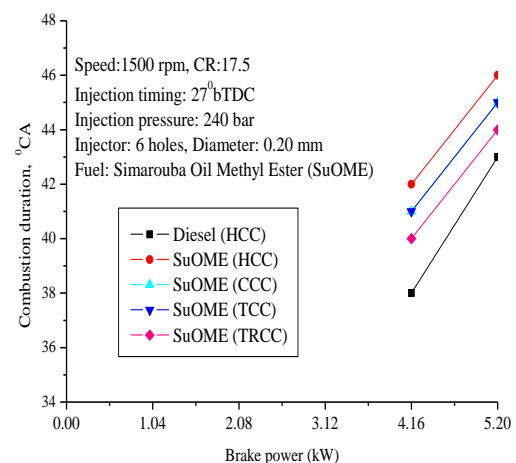


Fig. 4. Variation of combustion duration with BP

3.1.2 Combustion duration

Combustion duration variation with BP for 80% and 100% loading conditions for both diesel and SuOME fuels is portrayed in Fig.4. It is determined by a period between the start of combustion (SOC) and 90% cumulative heat release. Combustion duration is higher as the output power increases due to increased injected fuel quantity into the cylinder. It is clearly monitored that combustion duration is 3° CA higher with SuOME than that of conventional fuel using HCC due to improper mixing of fuel with air. The major reason for improper mixing is due to high pressure, and higher

viscosity hence, requires extended time duration for combining of air and fuel and resulting in incomplete combustion with extended diffusion combustion period. Comparing with different combustion chambers, results obtained by TrCC has 1-2⁰CA lesser combustion duration than CCC, TCC and HCC respectively for engine operating with SuOME. This may be caused by the development in mixing of fuel with air due to improved squish. Considerably larger combustion rates with SuOME operation leads to greater exhaust gas temperatures and reduced efficiency than diesel fuel.

3.1.3 Cylinder peak pressure

The comparison of peak pressure with break power at 80% and 100% load for both diesel and SuOME fuels for different piston shapes operating under optimized engine parameters is shown in Fig. 5. It may be noticed that, Figure indicate that the peak pressure at 100% load for diesel with HCC is higher than any other CC shapes operated using SuOME. In a CI engine, peak pressure depends on the rate of combustion at the initial stages; pressure which is influenced by the quantity of fuel participated in the second phase of CI engine combustion. It is also influenced by the mixture preparation during ignition delay period. This clearly shows that peak cylinder pressure is lower for SuOME because of shorter ignition delay. The peak pressure for diesel operating at HCC is 84 bar while for SuOME fuel is 78 bar, using TrCC for SuOME the peak pressure achieved is 81 bar which is almost nearer to the diesel fuel.

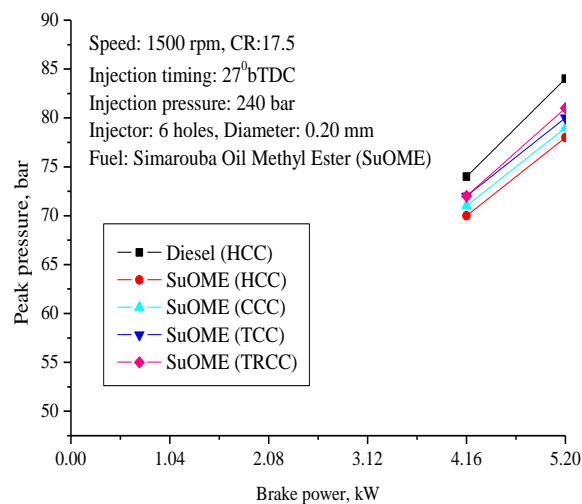


Fig. 5. Variation of cylinder peak pressure with BP

3.2 Performance Analysis

3.2.1 Break thermal efficiency

Break thermal efficiency of SuOME with different combustion chamber shapes for optimized engine parameters against engine break power is plotted in Fig. 6. It was noticed that BTE for conventional fuel operation was considerably greater than SuOME operation over all the load range. This may be characterized by lower calorific value and volatility of the SuOME. In addition, increased flame propagation is also accountable. The study with various CC shapes illustrated that for biodiesel operation; TrCC resulted in improved combustion leading to increased BTE by 1.26% compared to

HCC at 80% load. TrCC prevents the flame from extended over the squish band which results in higher mixture strength, superior air motion within cylinder and exhaust soot is reduced by increasing tumble and swirl motion. TrCC resulted in better performance compared to other CC.

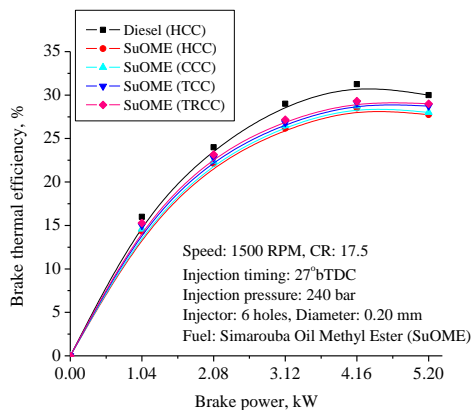


Fig. 6. Variation of BTE with BP

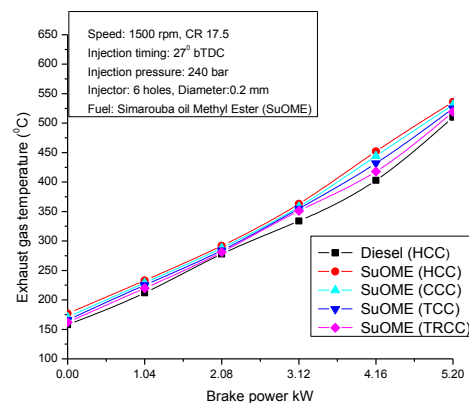


Fig. 7. Exhaust gas temperature with BP

3.2.2 Exhaust gas temperature

Variation of exhaust gas temperature of SuOME with engine load for different combustion chambers operating with augmented parameters is shown in Fig. 7. EGT is increased marginally with SuOME compared to diesel and the same trend is maintained for all the combustion chamber. The major cause for the higher EGT is the higher oxygen content in SuOME which results improvement in the combustion. Use of SuOME in HCC at 80% load gave exhaust gas temperature of 452°C which is 49°C higher than diesel. Exhaust gas temperature using TrCC is found to be 15°C higher than diesel fuel. The dissimilarity is that the EGT is less in engine operation with TrCC compared to CC shapes with respect to diesel is due to rapid air fuel mixing which leads to get quenching effect to the sprayed fuel.

3.3 Emission analysis

Different emission parameter measured for HCC, CCC, TCC, TrCC using SuOME biodiesel mode of operation are discussed in details in the following section.

3.3.1 Hydrocarbon emissions

Combustion chamber geometry influence on the HC emission for optimized operating conditions is clearly seen in Fig.8. HC emissions involve a fuel that is incompletely burned. HC refers to organic compounds of particulate matter in the state of gas. HC is formed due to deprived fuel distribution; greater amounts of excess air, lower EGT and part of fuel escaping into exhaust without burning. It was noticed that TrCC emit lesser HC levels compared to the operation with other the operation with CC shapes. This was due to improved combustion of SuOME as a result of better eddy formation and squish motion of air with TrCC. However, basic CC i.e., HCC may not give appropriate mixing of fuel with air leading to partial combustion. It may be due to detention in the substandard part of the bowl

by the vortex created with CC of HCC. From the graph it is observed that, using SuOME in TrCC reduces HC emissions by 6ppm than using conventional HCC. When compared to other combustion chambers TrCC gave reduced HC levels in all loading conditions.

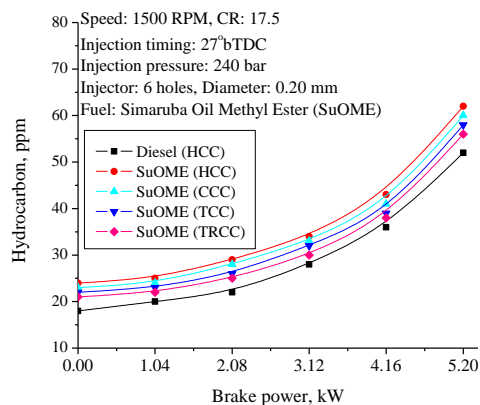


Fig. 8. Variation of Hydrocarbon with BP

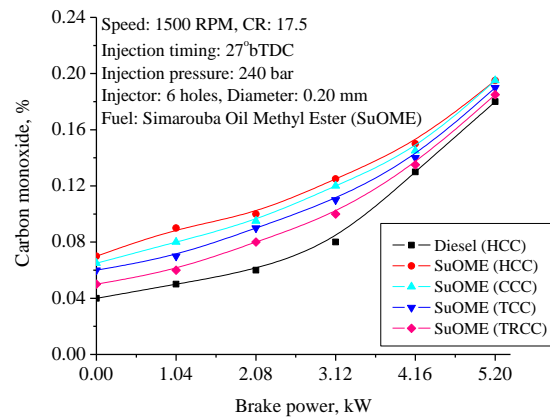


Fig. 9. Variation of Carbonmonoxide with BP

3.3.2 Carbon monoxide emissions

Fig. 9 presents the variation of CO emissions with BP for different combustion chambers operating with SuOME for optimized condition. CO emission level for SuOME biodiesel is higher compared to diesel operation for all the combustion chamber shapes. Incomplete combustion of SuOME is main reason for this trend. Incomplete combustion of carbon leads to form CO and it is indirect measure of combustion efficiency. The formation of CO is due to insufficient oxygen to form CO_2 , fuel property like higher viscosity, lower heating value and less adiabatic flame temperature. However TrCC resulted in reduced CO emission level compared with other CC shapes. This may be caused by increased disordered motion of air and elevated temperature dominant in the CC that lead to reduced heat losses for the cylinder wall and improved oxidation of CO and hence lowered emission levels. However, other CCs may not give appropriate mixing fuel combinations. From the plot is clear that the difference in CO emissions between the combustion chambers will be higher at lower loads and almost same at higher loads.

3.3.3 Smokeopacity

The smoke formation mainly results from the partial burning of the hydrocarbons and incomplete reacted carbon content in the injected fuel. Smoke is a solid soot constituent part suspended in tail pipe exhaust gas. The results of smoke opacity with BP are depicted in Fig.10. The smokeopacity also increases as the engine load increases. This is mainly due to more amount of fuel injected inside the cylinder. It is observed that the smoke opacity for SuOME biodiesel is higher than diesel throughout the load range. This may be attributed to large fatty acid content of SuOME, higher viscosity and slower burning of fuel as a result of deprived mixture formation. However, TrCC gives lesser smoke emission level compared with HCC, CCC, and TCC due to higher turbulence which gives good combustion and oxidation of soot particles.

3.3.4 Oxides of nitrogen emission

Fig. 11 presents the oxides of nitrogen variation with break power for SuOME biodiesel fuel and diesel fuel operated for different combustion chambers at optimized engine parameters. NO_x emission is appreciably influenced by the gas temperature and oxygen availability during combustion. From the plot it is observed that NO_x emission levels are bit higher for diesel fuel operation compared to biodiesel over the entire load range. This is caused by the amplified heat release rate during premixed combustion stage with diesel compared with SuOME operation. NO_x emissions are slightly amplified in TrCC compared to all other CC shapes tested. This could be caused by considerable improvement in the fuel burning that occurs due to uniform mixing. Rich oxygen content in the biodiesels is also accountable for this trend. Therefore it also results in amplified peak cycle temperature.

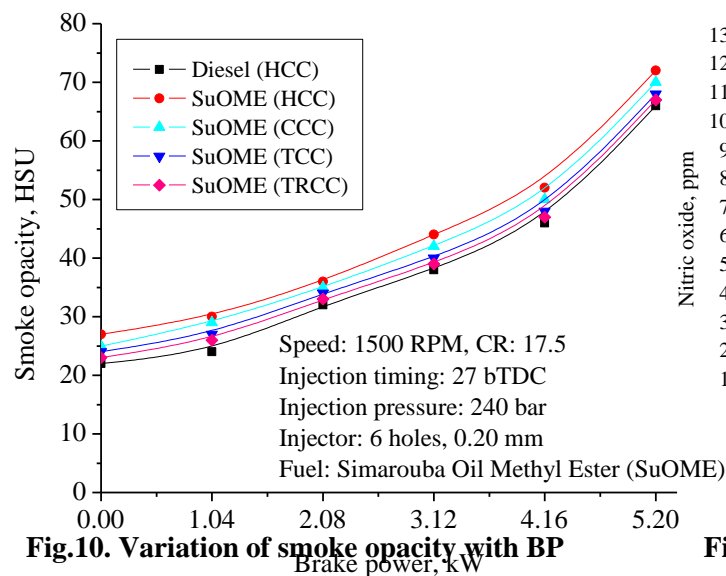


Fig.10. Variation of smoke opacity with BP

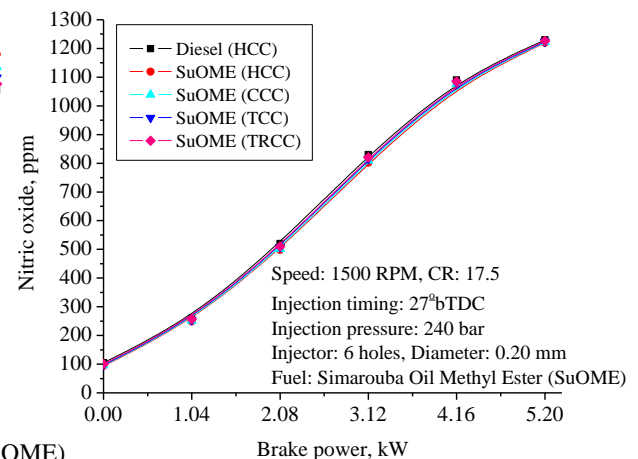


Fig.11. Variation of Nitric oxide with BP

Conclusions

An Extensive experiments were conducted on the utilization of biodiesel derived from Simarouba oil in single cylinder DI diesel engine with different CC shapes for an optimized parameters such as injection pressure, nozzle geometry, injection timing, number of nozzle holes. The overall combustion of SuOME was analysed and compared with conventional fuel. The following conclusions were drawn based on the experimental results.

- Simarouba biodiesel can be used in place of diesel in the single cylinder 4 stroke CI engine with little engine modification.
- Use of Simarouba biodiesel resulted into reduced engine performance with increased emissions when compared with diesel operation. However the performance of TrCC was found higher than HCC, CCC, and TCC with reduced emission levels.
- Better fuel air mixing and efficiency was observed with TrCC compared with other combustion chamber shapes because of induced turbulence.
- Ignition delay period was reduced by 0.3°CA using TrCC than HCC when operated with SuOME.
- The break thermal efficiency of TrCC is 1.3% higher than HCC, while 1% lower compared with diesel fuel operated with HCC.

- The smoke emissions is found to be about 7% lesser for TrCC than HCC and 1.5% higher than base engine operation.

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