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Different Injection Strategies to Enhance the Performance of Diesel Engine Powered with Biodiesel Fuels

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ABSTRACT

The compression ignition (CI) engines are most efficient and robust but they rely on depleting fossil fuel. Hence there is a speedy need to use alternative fuels that replaces diesel and at the same time engine should yield better performance. Accordingly, honge oil methyl ester (BHO) and cotton seed oil methyl ester (BCO) were selected as an alternative fuel to power CI engine in the study. In the first part, this paper aims to evaluate best fuel injection timing (IT) and injector opening pressure (IOP) for the biodiesel fuels (BDF). The combustion chamber (CC) used for the study is toriodal re-entrant (TRCC). The experimental tests showed that BHO and BCO yielded overall better performance at IT of 19° before top dead centre (bTDC) and IOP of 240 bar. In the second part, the effect of number of holes on the performance of BDF powered CI engine was studied keeping optimized IT and IOP. The six-hole injector with 0.2 mm injector orifice diameter yielded better performance compared to other injectors of different holes and size tested.

Keywords: Honge biodiesel (BHO), Cotton seed biodiesel (BCO), Toriodal Re-entrant Combustion Chamber (TRCC), number of holes, performance

INTRODUCTION

The greenhouse gas (GHG) emissions and fuel consumption of IC engines are the two major worldwide environmental and energy challenges. The vegetable oils are non-toxic, biodegradable, environmental friendly, renewable and also, they yield lower engine out gases. A wide range of plants (more than 300 species) yielding oil seeds can be grown to get both edible and nonedible oils from which biodiesel fuel (BDF) could be produced (Planning Commission of India, 2006; Jain et al., 2011). Employment of edible oils for CI engine units is not encouraged worldwide due to their great demand for human consumption (Banapurmath et al., 2008; No, 2011; Rao, 2011). Serious engine fouling was observed in the CI engine operation due to the incomplete fuel combustion and thereby carbon deposition on the injector tip and valve seat were observed (Mishra and Murthy, 2010). Hence the direct use of vegetable oils is not recommended for CI engines.

LITERATURE REVIEW

The CI engine run with flax, cotton seed and palm oil BDF yielded less brake power (BP), high brake specific fuel consumption (BSFC), lower carbon monoxide (CO) and smoke emissions with slight increase in engine out oxides of nitrogen (NO_x) emissions (Shehata, 2013). The experimental work with Annona methyl ester blends at different fuel IT showed 6.4% higher brake thermal efficiency (BTE) at 33° bTDC and 11.9% lower fuel consumption compared to original IT 27° bTDC (Senthil et al., 2016). Experimental work on multi cylinder CI engine run on Moringa Oleifera BDF B10 and B20 with speeds ranging from 1000–4000 rpm at full load conditions revealed that the BP was lower and BSFC was higher for both B10 and B20 BDF compared to diesel due to increase in frictional losses and increase in time for heat transfer to the cylinder wall at all speeds tested (Mofijur et al., 2014). The tests to investigate the performance, emission and heat release rate (HRR) of karanja BDF and its blends powered CI engine showed similar BTE for all the blends at higher loads. On the other hand, the higher values of BDF blends showed lower BTE at lower loads (Dhar and Agarwal, 2014). A engine test with waste cooking oil B(50) from restaurants showed 19.2% increase in BTE, 52% reduction in hydrocarbon (HC) emission, 37.5% reduction in CO emissions and 36.84% increase in NO_x emissions (El-Kassaby and Nemit-allah, 2013).

The combined impact of IOP and CC geometry on the performance of Pongamia oil methyl ester (POME) fuelled diesel engine was studied and reported that the toriodal re-entrant combustion chamber (TRCC) resulted in higher BTE with improved BSFC at higher IOP (Jaichandar and Annamalai, 2013). The effect of CC shapes & injection strategies on the performance of Uppage oil methyl ester (UOME) fuelled CI engine was studied and results showed that toriodal CC (TCC) was best to yield better engine performance at fuel IT of 19° bTDC using injector of 6 hole and 0.18 mm diameter (Basavarajappa et al., 2014). The tests were performed on CI engine operating with waste plastic oil at 4 fuel IT selected (23°, 20°, 17° and 14° bTDC). The retarded fuel IT of 14° bTDC resulted in lower NO_x, CO and HC emissions with higher BTE, carbon dioxide (CO_2) and smoke levels at all the test conditions in comparison to fuel IT of 23° bTDC (Mani and Nagarajan, 2009). The experimental investigation on CI engine with honge oil methyl ester (HOME) and producer gas (PG) showed 4–5% higher BTE and reduced emission levels when re-entrant type CC and IOP of 230 bar, 4 hole and 0.25 mm nozzle orifice were used (Yaliwal et al., 2016).

The neat Polanga BDF (PB100) provided maximum peak cylinder pressure (PP) (6.61 bars higher than that of mineral diesel). The ignition delay (ID) were consistently shorter for JB100 (varying between 5.9° and 4.2° crank angle (CA)), KB100 (varying between 6.3° and 4.5° CA) and PB100 (varying between 5.7° and 4.2° CA) lower than mineral diesel (Sahoo et al., 2007). The tests with the Sal methyl ester (SME) and its blends in a single-cylinder four-stroke diesel engine appraised performance like BTE and SFC, lowered emissions like CO, HC and smoke. The cumulative heat release of SME10 was slightly higher than baseline value (Pali and Kumara, 2016). Biodiesels have lower BTE, much higher BSFC and higher heat losses except the exhaust heat loss than mineral diesel fuel (Abedin et al., 2013). Engine consumes more BDF in comparison to the diesel fuel because of its lower energy content and cost has raised by using BDF as an alternative for diesel (Sadeghinezhad et al., 2013; Park et al., 2012). The CI engine running at lower load and speed (high idling condition) showed the increased SFC and NO_x emission with JOME compared to diesel but lower amount of CO and HC emissions in the engine out gas (Rahman et al., 2014).

The objective of this current study is to test the locally available BDF for CI engine application (**Figure 1**) and to improve their performance in terms of higher BTE and lower exhaust emissions with different injection strategies.

EXPERIMENTAL DETAILS

Fuels Used

In the current study, BHO and BCO BDF derived from the locally available honge oil and Cotton seed oils. The properties of BHO and BCO were measured at Bangalore Test House Laboratory, Bengaluru, India. The properties of the fuels used are given in **Table 1**.

Experimental Procedure

Initially the experimental tests were carried out on CI engine at the engine speed of 1500 RPM at different loading conditions to obtain best BTE conditions. The readings recorded only after engine attained stable condition. The volumetric fuel flow rate of all fuels used was measured using a burette and stopwatch method. Here the time taken for fuel flow of 100 ml was recorded and used for further calculations. Next the experiments were conducted only at 80% load using diesel, BHO and BCO fuels with 3-, 4-, 5- and 6-hole injectors. Further experiments were conducted by varying the hole size of 6-hole injector. Specifications of the CI engine test rig used for the experimental study are shown in **Table 2**. Engine cooling was achieved by applying circulating water through the jackets of the engine and cylinder head. A piezoelectric transducer (Make: PCB Piezotronics, Model: HSM 111A22, Resolution: 0.145 mV/kPa) fitted to the cylinder head was utilized to measure the in-cylinder gas pressure. The heat release rate (HRR) of the fuel causes variation of gas pressure and temperature within the engine cylinder. The HRR was calculated using the procedure followed in literature (Hayes et al., 1986; Hohenberg, 1979).

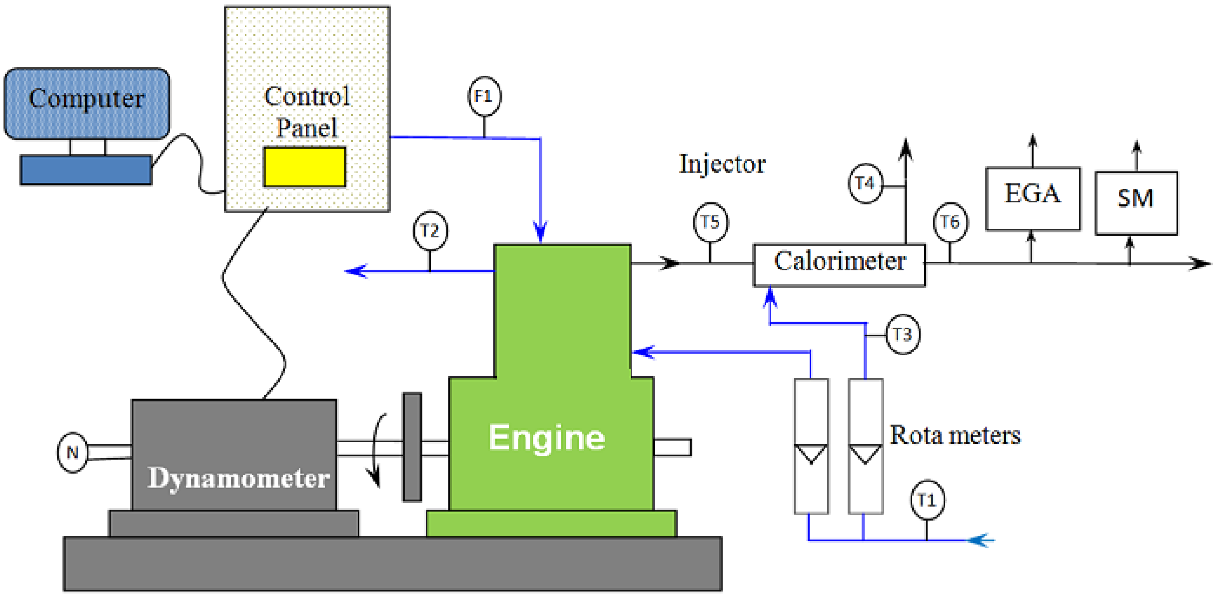

Figure 1. CI engine test rig used for the current experimental study
T1, T3: Intake Water Temperature. **T2**: Outlet Engine Jacket Water Temperature. **T4**: Outlet Calorimeter Water Temperature. **T5**: Exhaust Gas Temperature before Calorimeter. **T6**: Exhaust Gas Temperature after Calorimeter. **F1**: Fuel Flow DP (Differential Pressure) unit. **N**: RPM encoder. **EGA**: Exhaust Gas Analyzer. **SM**: Smoke meter.

Table 1. Properties of Diesel, BHO and BCO.

Sl. No.	Properties	Diesel	BHO	BCO	Standard limits Min.	Standard limits Max.	ASTM standard
1	Viscosity (cSt at 40°C)	4.59	5.6	5.0	1.9	6	ASTM D445
2	Flash point (°C)	65	163	167	100 –	-	ASTM D93 D3278 - 96
3	Calorific Value (kJ/kg)	45000	36010	39648	-	-	ASTM D5865
4	Density (kg/m3 at 15 °C)	830	890	885	860	900	ASTM D4052
5	Cloud Point (°C)	-10	-2	-3	-	-	ASTM D2500
6	Pour Point (°C)	-2	1	2	-	-	ASTM D97
7	Cetane Number	50	42	45	47	-	ASTM D613
8	Cold Filter Plugging Point (°C)	4	5	6	-	-	ASTM D6371
9	Moisture (%)	0.02	0.02	0.02	-	0.05	ASTM D2709
10	Carbon Residue (%)	0.1	0.12	0.13	-	0.05	ASTM D4530

The start of combustion process was determined from the differentiated cylinder gas pressure variation time data where a sudden rise in the slope at the point of ignition due to the sudden high premixed heat release. The end of combustion process was taken as the point where 90% of the heat release had occurred (calculated from the cumulative heat release curve). The ID is the time lag between the start of injection and the start of ignition. The start of injection was obtained based on the static fuel IT. Exhaust gas composition during the steady-state operation was measured by employing a Hartridge smoke meter shown in Figure 2 and five-gas analyzers (A DELTA 1600 S-non-dispersive infrared analyzer) shown in Figure 3. Figure 4 shows the Toroidal Reentrant Combustion Chamber (TRCC) used for the current experimental study.

Table 2. CI Engine specifications.

Sl No	Parameters	Specification
2	Type	TV1 (Kirloskar make)
3	Software used	Engine soft
4	Nozzle opening pressure	200 to 225 bar
5	Governor type	Mechanical centrifugal type
6	No. of cylinders	Single cylinder
7	No. of strokes	Four stroke
8	Fuel	H. S. Diesel
9	Rated power	5.2 kW (7 HP at 1500 RPM)
10	Cylinder diameter (Bore)	0.0875 m
11	Stroke length	0.11 m
12	Compression ratio	17.5 : 1
Air Measurement Manometer:		
13	Made	MX 201
14	Type	U- Type
15	Range	100 – 0 – 100 mm
Eddy current dynamometer:		
16	Model	AG – 10
17	Type	Eddy current
18	Maximum	7.5 (kW at 1500 to 3000 RPM)
19	Flow	Water must flow through Dynamometer during the use
20	Dynamometer arm length	0.180 m
21	Fuel measuring unit – Range	0 to 50 ml

Figure 2. Hartridge Smoke meter.

Figure 3. Exhaust gas analyzer.

Figure 4. Toroidal Reentrant Combustion Chamber used.

Table 3. The accuracies of the measurements and the uncertainties in the calculated output parameters.

Measured variable	**Accuracy (±)**
Load, N	0.1
Engine speed, rpm	4
Temperature, °C	1
Fuel consumption, g	0.1
Measured variable	**Uncertainty (%)**
HC	±5
CO	±2.5
NOx	±2.3
Smoke	±1.3
Calculated parameters	**Uncertainty (%)**
BTE, %	±1.2
HRR, J/°CA	±1.0

Uncertainty Analysis of the Experimental Data

The accuracies of the measurements and the uncertainties in the calculated parameters of the current investigation are provided in the **Table 3**. In order to minimize the errors of physical parameter measurements six readings were recorded and averaged out results are only presented for the analysis.

RESULTS AND DISCUSSIONS

This section discusses the experimental results of compression ignition (CI) engine powered with diesel, BHO and BCO with different injection strategies and number of holes. Different injection strategies used were fuel IT, different IOP, conventional fuel injectors with different number of holes and sizes.

Effect of Injection Timing on the Performance of CI Engine

Experimental studies on the BDF fuelled CI engine at three IT of 19°, 23° and 27° bTDC was carried out with CR of 17.5. The injector for initial experimentation used was of 3-holes with hole size 0.3 mm diameter. The normal IOP of 205 bar was selected for the study to inject all liquid fuels. Engine was always run at rated speed of 1500 rpm.

Performance in Terms of Brake Thermal Efficiency

The effect of the fuel IT on the BTE of CI engine powered with BHO and BCO with brake power (BP) is shown in **Figure 5.** At 80% load, the highest BTE of 31.25% was obtained with mineral diesel fuel at an IT of 23° bTDC and IOP of 205 bar. However maximum BTE achieved with BHO and BCO powered CI engine operation

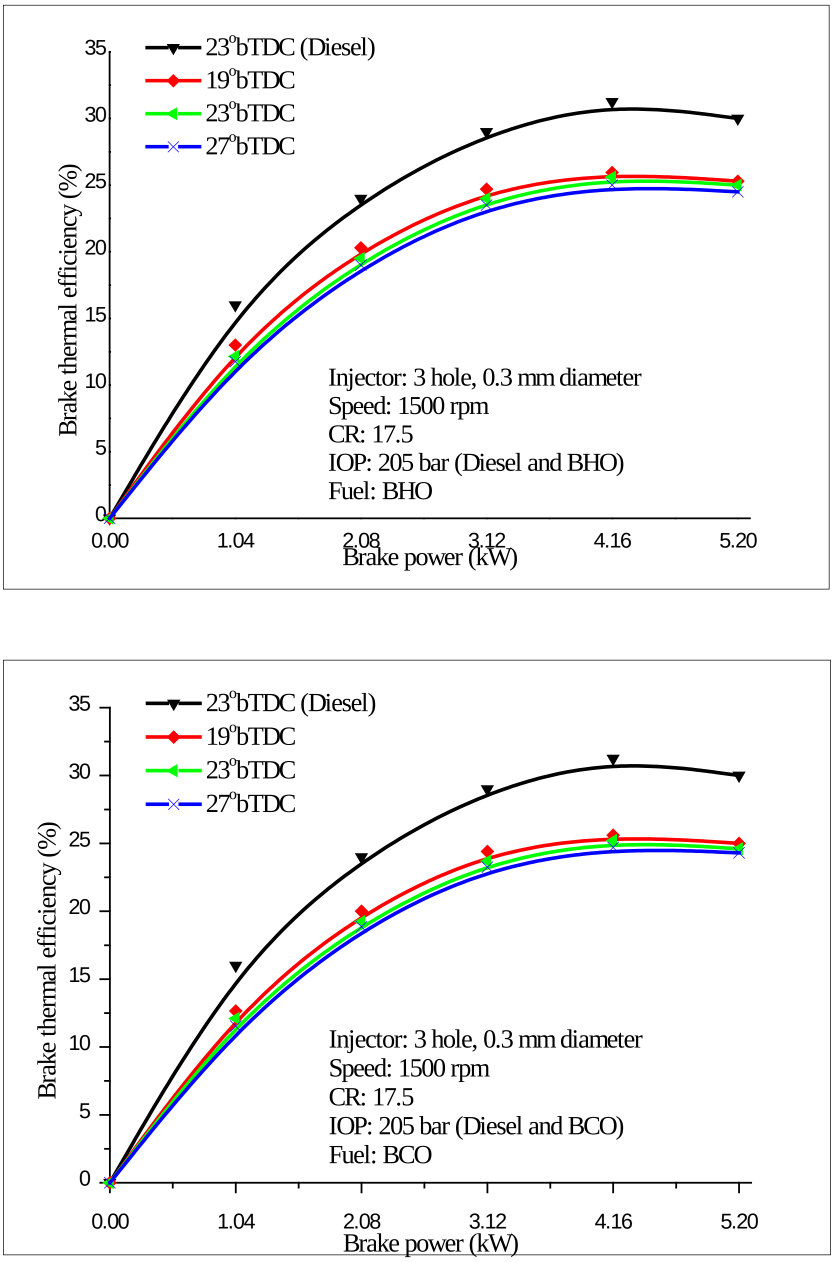

Figure 5. Effect of the IT and BP on the BTE for BHO/BCO.

at 19° bTDC was lower by 17% and 18.1% respectively compared to mineral diesel operation. The BTE of the BHO/BCO fuelled CI engine operations were lower compared to diesel at all the three IT. The decrease in BTE of the engine fuelled with BDF might be attributed to the lower energy content of these BDFs and higher specific fuel consumption (SFC). Also, higher viscous nature of BDFs resulted into poor formation of the homogeneous mixture in comparison with mineral diesel and hence inferior BTE. Best BTE was achieved with IT of 19° bTDC for BHO/BCO.

Effect of Injector Opening Pressure (IOP) on the Performance of CI Engine

Effect of variation in IOP on the performance of diesel engine powered with BHO/BCO was studied where in IOP varied from 220 to 260 bar. The injector of 3 holes with a hole diameter of 0.3 mm was used for the experimental study. During the experimentation, engine operating parameters such as fuel IT and CR were kept constant at 19° bTDC and 17.5 respectively.

Performance in Terms of Brake Thermal Efficiency

The effect of different IOP on the BTE of CI engine at different loads is shown in **Figure 6**. Amongst all the IOPs, the highest BTE occurred at 240 bar. This could be due to better atomization and fuel mixing with air, resulting in improved combustion. A higher IOP (260 bar) led to wall wetting which reduced the BTE. The

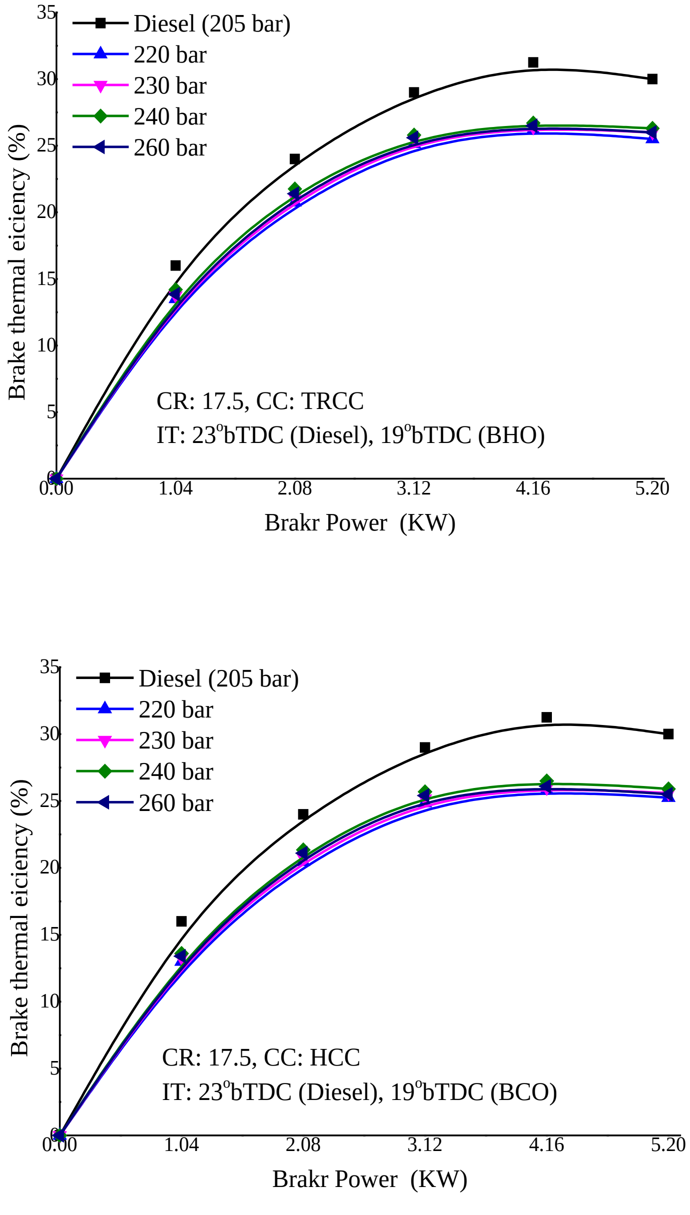

Figure 6. Effect of the IOP and BP on the BTE for BHO/BCO.

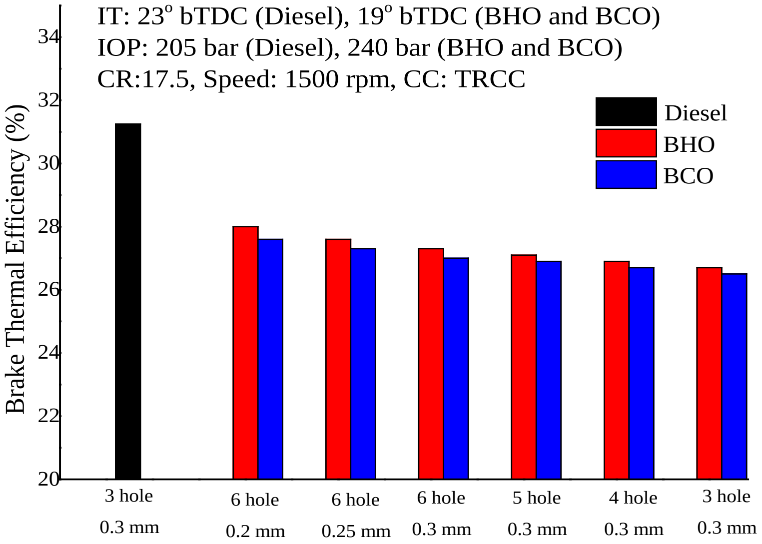

Figure 7. Effect of different nozzle orifice size on BTE for BHO/BCO.

maximum BTE achieved for BHO and BCO was found to be 26.7% and 26.5% respectively at 80% load at an IOP of 240 bar.

Effect of Nozzle Orifice Size on the Performance of CI Engine

This section presents the performance of BHO and BCO powered CI engine using a 6-hole nozzle with different nozzle orifice diameter. In order to study the effect of nozzle orifice diameter on the BDF powered engine performance, 6 holes nozzle with 0.2 mm, 0.25 mm and 0.3 mm were selected. Results of 6 holes nozzle with different orifice size were compared with a nozzle having 3, 4 and 5 holes of 0.3 mm orifice diameter. During the experimentation, the fuel IT, IOP, CR and speed were kept constant. The readings reported are at 80% load only. The fuel IT and IOP were kept at best BTE condition obtained.

Performance in Terms of Brake Thermal Efficiency

Figure 7 shows variation of BTE of the engine operated with BHO and BCO using a 6-hole injector of different orifice diameter. Smaller diameter nozzle resulted in better fuel atomization, mixing of air with fuel inside the CC and this further led to better combustion and hence higher levels of BTE. A 6-hole nozzle having an orifice of 0.2 mm resulted in better BTE compared to all other nozzles selected for the study, this could be mainly attributed to enhanced fuel-air mixing. Nozzle of 6 holes yielded lesser penetration distance of fuel due to lower mass low rate of fuel per hole which reduced wall wetting there by resulted in increased BTE. The BHO gave better results compared to BCO at all injection strategies. Maximum BTE achieved was 28% and 27.6% respectively for BHO and BCO operation by 6 hole injector with 0.2 mm orifice diameter.

Performance in Terms of Engine Out HC and CO Emission

Variation of HC and CO for the diesel, BHO and BCO with varying nozzle orifice size is shown in **Figure 8** and **Figure 9**. It may be noted that higher HC and CO emissions in the exhaust gas are the direct result of incomplete combustion of fuels. The HC and CO emissions were found to be lower for smaller nozzle hole size compared to bigger ones with BDFs. A 6-hole nozzle with 0.2 mm hole diameter resulted better performance compared to all nozzles of different hole sizes, however these results were higher compared to mineral diesel fuel under study. Nozzle of 6 holes yields lesser penetration distance of fuel due to lower mass low rate per hole which reduced wall impingement there by resulted in decreased HC and CO emissions. The reason could be the higher viscosity and higher density of BDFs. Another reason could be attributed to higher BTE achieved with diesel.

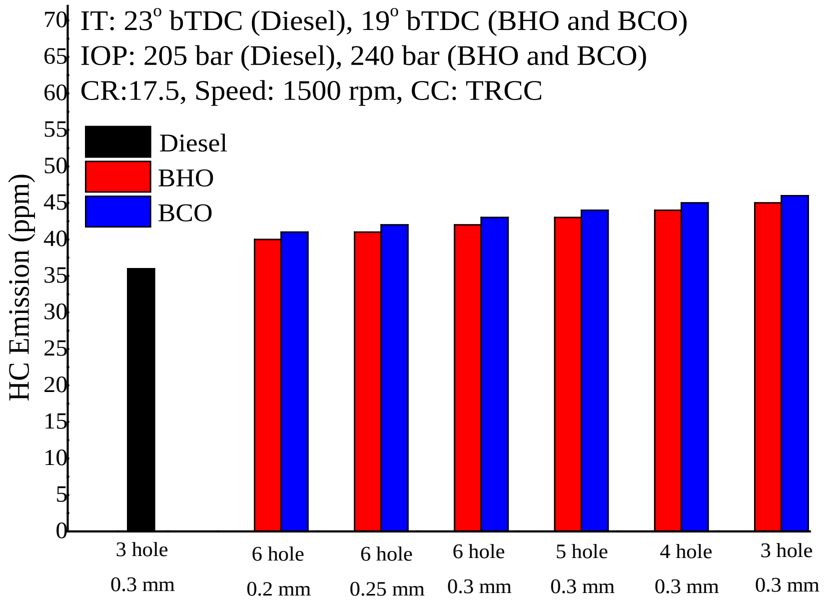

Figure 8. Effect of different nozzle orifice size on HC emission for BHO/BCO.

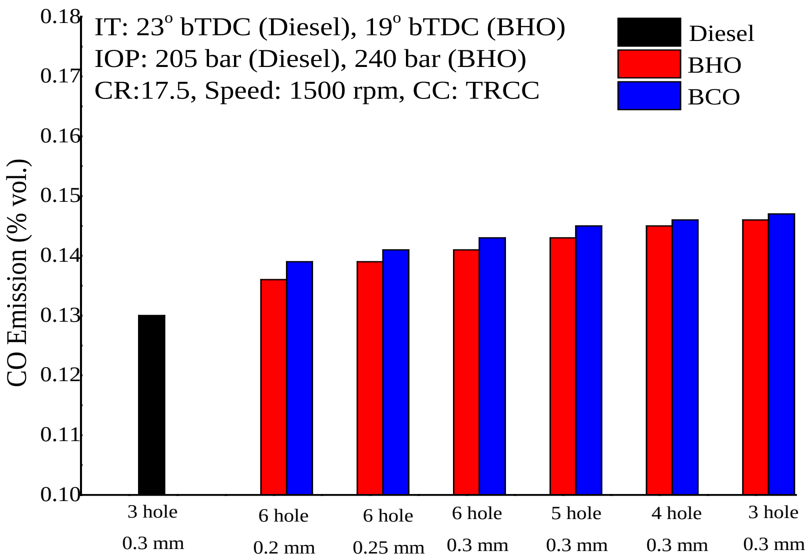

Figure 9. Effect of different nozzle orifice size on CO emission for BHO.

Performance in Terms of Engine out NO_x Emission

Figure 10 shows the variation in the NO_x emission with 0.2 mm, 0.25 mm and 0.3 mm orifice size of 6-hole nozzle for BHO and BCO. The variations in NO_x emission follow changes in adiabatic flame temperature. The reason for increased NO_x emission with decreased size of holes could be due to better mixture and combustion prevailing inside the engine cylinder and more heat released during premixed combustion. Nozzle of 6 holes with 0.2 mm diameter resulted in higher NO_x emission compared to 3-, 4- and 5-hole nozzle, the reason could be higher combustion temperature existed inside the CC. The BHO showed higher NO_x compared to BCO as it has better combustion qualities.

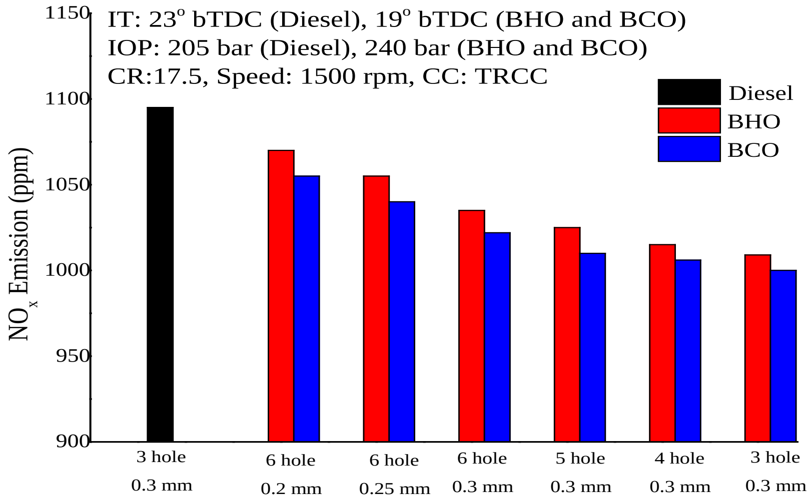

Figure 10. Effect of different nozzle orifice size on NO_x emission for BHO/BCO.

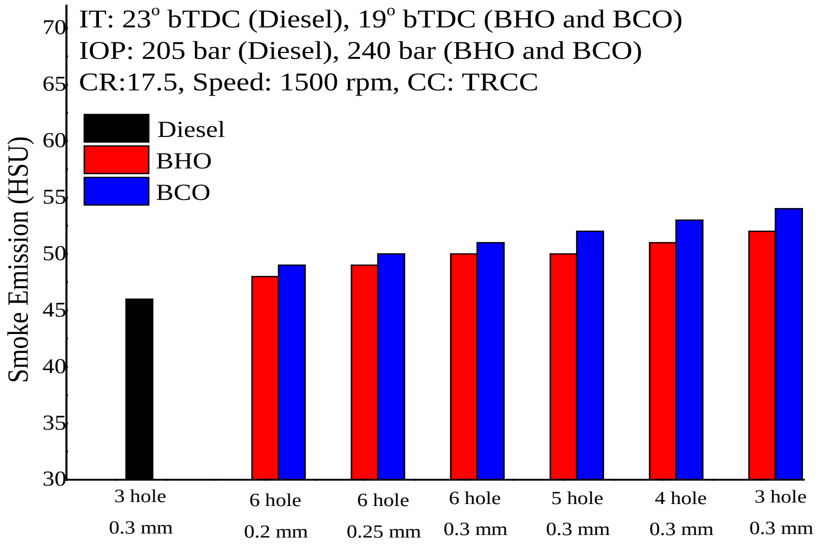

Figure 11. Effect of different nozzle orifice size on smoke emission for BHO/BCO.

Performance in Terms of Engine Out Smoke Emission

Variation of smoke emission for the diesel, BHO and BCO with varying nozzle orifice size is shown in Figure 11. It may be noted that higher smoke emissions in the exhaust gas are the direct result of incomplete combustion of fuels. The smoke emissions were lower for smaller nozzle hole size compared to bigger ones with BDF. A 6-hole nozzle with 0.2 mm hole diameter resulted better performance compared to all nozzles of different hole sizes, however these results were higher compared to mineral diesel fuel. Nozzle of 6 holes yields lesser penetration distance of fuel due to lower mass low rate per hole which reduced wall impingement there by resulted in decreased smoke emissions on account of complete combustion.

Combustion characteristics

The combustion characteristics of CI engine powered with BHO and BCO BDF at engine operating parameters are explained in this section.

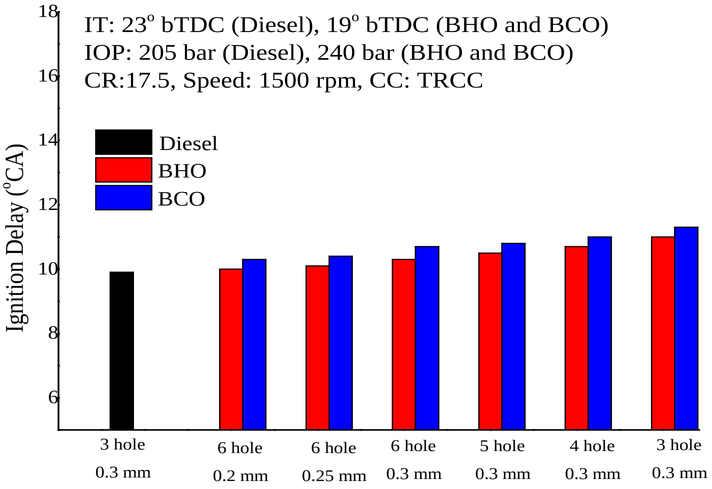

Figure 12. Variation in ID with number of injector holes and different hole size for BHO/BCO.

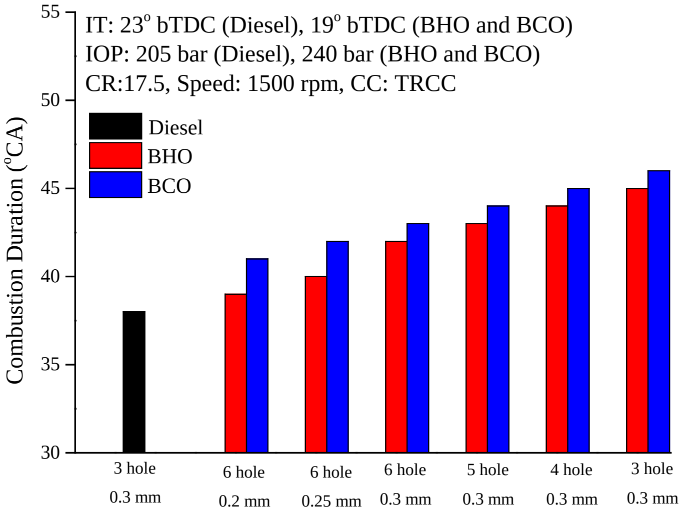

Figure 13. Variation in CD with number of injector holes and different hole size for BHO/BCO.

Ignition Delay (ID)

The variation of ID with different TRCC and BP is shown in Figure 12. The ID is calculated based on the static IT using pressure crank angle history for 100 cycles. Decreasing trend of ID was seen with increase in number of injector holes and smaller sized orifice. It could be attributed to better air-fuel mixing and increased combustion temperature and better combustion. However, the ID for diesel was lower compared to BDF powered engine operation.

Combustion Duration (CD)

The variation in CD shown in Figure 13 was calculated based on the duration between the start of combustion (SOC) and 90% cumulative heat release. The total CD is the period of the overall burning process and it is the sum of flame development period and rapid combustion period. Higher CD was observed with BDF compared to diesel operation. It might be due to higher viscosity of biodiesels led to improper air–fuel mixing, lower gas temperature and pressure. However, CD was reduced with increase in number of injector holes and smaller sized orifice. The CD for BHO and BCO found to be 39 and 41 J/°CA respectively for six-holes injector with 0.2 mm orifice diameter against 38 J/°CA for diesel with 3 holes injector and 0.3 mm orifice size.

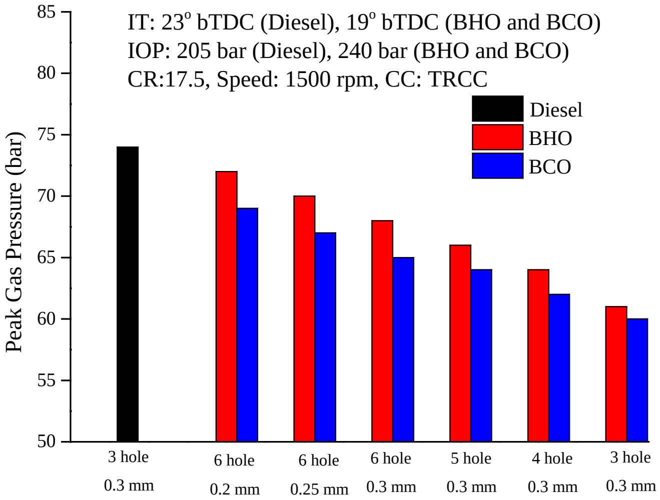

Figure 14. Variation in PP with number of injector holes and different hole size for BHO/BCO.

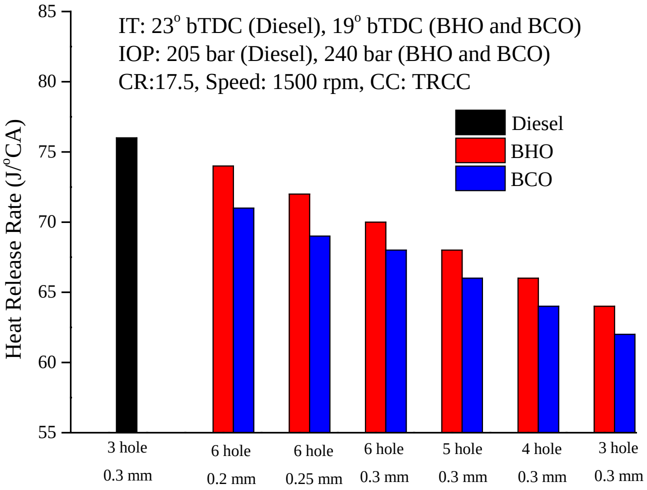

Figure 15. Variation in HRR with number of injector holes and different hole size for BHO/BCO.

Cylinder Gas Peak Pressure

Figure 14 indicates the variation in cylinder gas peak pressure for BHO and BCO. The PP depends on the combustion rate and amount of fuel consumed during rapid combustion period. Slower burning nature of BDF during the ID period could be responsible for lower PP compared to mineral diesel. The BHO and BCO with TRCC resulted in higher in-cylinder pressure as the number of holes increased and hole size decreased. It could be due to the combined effect of ID and slightly higher adiabatic flame temperature. The PP for BHO and BCO found to be 72 and 69 bar respectively for six holes injector with 0.2 mm orifice diameter against 74 bar for diesel with 3 holes injector and 0.3 mm orifice size.

Heat release rate (HRR)

Figure 15 depicts the variation in HRR with number of injector holes and hole size. The BDF powered CI engine operation resulted into higher HRR with injector of more number of holes and smaller sized orifice. Better air fuel mixture, better combustion, higher cylinder gas temperature and pressure prevailed might be the reason for the higher HRR with TRCC. The BDF showed lower HRR compared to mineral diesel due to their poor combustion qualities. The HRR for BHO and BCO found to be 74 and 71 J/°CA respectively for six holes injector with 0.2 mm orifice diameter against 76 J/°CA for diesel with 3 holes injector and 0.3 mm orifice size.

CONCLUSIONS

The following critical conclusions could be drawn from the experimental results obtained from CI engine operated with toriodal combustion chamber at compression ratio of 17.5 and engine speed of 1500 rpm:

- The engine powered with BDF yielded best BTE at fuel IT of 19° bTDC and IOP of 240 bar.
- The BHO showed better performance compared to BCO due to better combustion quality and lower viscosity.
- Six holes injector provided better results compared to injector of other holes selected for the study. Further the injector of six holes with 0.2 mm orifice diameter yielded better results compared to 0.25 mm and 0.3 mm orifice diameter.
- The BDF showed 10-12% lower BTE with the injector of six holes with 0.2 mm orifice diameter.
- The BDF showed 11-14% higher HC and 2-7% higher CO emissions with the injector of six holes with 0.2 mm orifice diameter.
- The BDF showed 2-4% lower NO_x emissions with the injector of six holes with 0.2 mm orifice diameter.
- The BDF showed 3-9% lower PP and HRR emissions with the injector of six holes with 0.2 mm orifice diameter.
- The BDF showed 2.6-8% higher ID and CD emissions with the injector of six holes with 0.2 mm orifice diameter.

Overall the engine operation was smooth with neat BDF with no hardware modification. An injector of six holes with 0.2 mm orifice diameter yields better performance when engine powered with BDF and the results found are close to one observed with injector of 3 holes and 0.3 mm orifice diameter when engine powered with diesel.

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