

Effects of hydrogen flow rate, injection pressure and EGR on performance of common rail direct injection (CRDi) engine in dual fuel mode

Effects of
hydrogen flow
rate

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Abstract

Purpose – The different performance tests were conducted on diesel engine compression ignition (CI) mode and CRDi engine.

Design/methodology/approach – The CI engine was suitably modified to CRDi engine with Toroidal re-entrant combustion chamber (TRCC) and was run in dual-fuel (DF) mode. Hydrogen (H₂) was supplied at different flow rates during the suction stroke, and 0.22 Kg/h of hydrogen fuel flow rate (HFFR) was found to be optimum. Diesel and biodiesel were used as pilot fuels. The CRDi engine with DF mode was run at various injection pressures, and 900 bar was found to be optimum injection pressure (IP) with 10o before top dead center (bTDC) as fuel injection timing (IT).

Findings – These operating engine conditions increased formation of oxides of nitrogen (NO_x), which were reduced by exhaust gas recycle (EGR). With EGR of 15%, CRDi engine resulted in 12.6% lower brake thermal efficiency (BTE), 5.5% lower hydrocarbon (HC), 7.7% lower carbon monoxide (CO), 26% lower NO_x at 80% load as compared to the unmodified diesel engine (CI mode).

Originality/value – The current research is an effort to study and evaluate the performance of CRDi engine in DF mode with diesel-H₂ and BCPO-H₂ fuel combinations with TRCC.

Keywords Hydrogen (H₂), Biodiesel of ceiba pentandra (BCPO), Hydrogen flow rate (HFR), Exhaust gas recirculation (EGR)

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Nomenclature

Diesel-H ₂ DF mode	Diesel hydrogen dual-fuel mode	BSFC	Brake-specific fuel consumption
BCPO-H ₂ mode	Biodiesel of Ceiba Pentandra hydrogen dual-fuel mode	BTE DF IT	Brake thermal efficiency Dual fuel Injection timing
BCPO	Biodiesel of Ceiba Pentandra	IP CRDi	Injection pressure Common rail direct injection
HFR	Hydrogen flow rate		
HRR	Heat release rate	EGR	Exhaust gas recirculation
PP	Peak pressure	NG	Natural gas
CD	Combustion duration	LPG	Liquefied petroleum gas
ID	Ignition delay	CNG	Compressed natural gas
HC	Hydrocarbon	HCCI	Homogeneous charge compression ignition
CO	Carbon monoxide		
NO _x	Oxides of nitrogen	TRCC	Toroidal re-entrant combustion chamber

1. Introduction

The fast exhaustion and higher prices of fossil fuel besides environmental legislations, biofuels have been proven the potential replacement for internal combustion engine fuel. Diesel engine dominates in the automotive sector and power generation applications because of its favorable good energy efficiency, reliability, and durability, but exhaust emissions are a matter of concern, especially control of NO_x. Dual-fuel (DF) engines have advantage of lower exhaust emissions and improved performance (Abedin *et al.*, 2016; Bora and Saha, 2016; Kumar *et al.*, 2017). Use of hydrogen as fuel especially at lower and medium engine loads in a heavy-duty H₂-diesel DF engine operates well with H₂ composition of 98 and 85% respectively. Exhaust gas recirculation (EGR) supplied in the engine led to decrease in the NO_x emission by 75% (Dimitriou *et al.*, 2018). The H₂ energy shares vary from 0% to 55% with port fuel injector that injects into the intake manifold. As the H₂ share increases, there is a decline in NO_x emissions but increased with compression ratio (CR) (Sharma and Dhar, 2018). A diesel engine operated at an engine speed of 1,500 rpm by using eucalyptus methyl esters and natural gas (NG) by supplying H₂ at different flow rates in DF mode. The variation of NG and H₂ quantity keeping eucalyptus biodiesel constant showed brake-specific fuel consumption (BSFC) reduction by 10% with 25% H₂ blend. An increase in heat release rate (HRR) was observed along with increase in peak pressure (PP) when the engine was enriched with NG and H₂. The shorter ID was attributed for increased HRR and PP (Tarabet *et al.*, 2018).

H₂, producer gas and mixture of both are used along with diesel as pilot fuel in a DF mode of operation. For H₂ substitution up to 30%, the maximum pressure rise rate increases and decreases for further substitution of H₂, for all loading conditions. A similar trend is found with the peak cylinder pressure for 13–40% loading condition, and a decrease in pressure is recorded for loads greater than 80%. HRR was found to decrease for both the fuel blends as compared to normal diesel operation (Dhole *et al.*, 2016). An experimental validation was provided for the NO_x model generation of H₂-diesel DF engine. Engine speed, equivalence ratio, H₂ energy share ratio, fuel injection timing (IT) and EGR are the parameters that are varied to perform the tests and build the model. The NO_x model developed is validated and could be used for further studies (Kumar *et al.*, 2018). H₂ added into the intake manifold of an H₂ diesel DF engine converted NO into NO₂. This formation takes place during the

postcombustion process. H₂ addition increased NO_x emissions in a significant way (Li *et al.*, 2018). Use of H₂ in an IC engine reduced the emissions of engine including CO as compared to an engine operating on fossil fuels (Tsuji-mura and Suzuki, 2017). Under higher loading conditions, with the addition of H₂ to biogas, the combustion patterns changed yielding higher HRR and PP, as compared to lower loads. The emission and performance characteristics remain unchanged for H₂ supplementation of 5% for all the loading conditions. Beyond 5% of H₂ addition resulted into better performance and lesser emissions of the engine (Verma *et al.*, 2018). A diesel engine is operated on DF mode with diesel + liquefied petroleum gas (LPG). The engine is modified suitably to run on DF mode with LPG as primary fuel and diesel as pilot fuel. An LPG carburetor is incorporated at the intake manifold, and engine tests at 1700 rpm under varying load conditions and different LPG proportions are carried out. The engine performance is better on solely diesel operation under loads of 35% while the performance is enhanced by using the DF mode for higher loads. The engine operation was better in DF mode at higher loads (Rao *et al.*, 2010). The LPG fuel is tested with five different blends of propane to butane blends as mentioned: 100:0, 70:30, 55:45, 25:75, 0:100. The fuel blend with 25% propane composition shows highest efficiency. For the composition of 55:45, a knock was experienced (Elnajjar *et al.*, 2013). For higher engine speeds, it is found that the in-cylinder pressure is also high and vice versa. Another finding reported is that the varying LPG mass fraction greatly affects the NO_x and hydrocarbon (HC) emissions. The emissions reduce as LPG content is raised (50–60%). A direct proportional relationship is found between the LPG fuel content and the output torque (Ngang and Abbe, 2018). Compressed natural gas (CNG) is used as low-reactivity fuel in this study. DF-PCCI with adopting the optimized charge control strategy, which used throttling and hot-EGR together, yielded reduced HC and CO emissions (Shim *et al.*, 2018). The engine is made to operate on methane–diesel DF mode that results in reduction in carbon dioxide (CO₂) emissions. The analysis reported that the model can be effective for light-duty applications (Belgiorno *et al.*, 2018). A small late injection had a little effect on in-cylinder pressure and HRR (Wu *et al.*, 2018). Addition of Al₂O₃ increased BTE by 15% and a reduction in BSFC by 12%. NO_x, CO and HC emissions were reduced greatly (El-Seesy *et al.*, 2018). Use of a diesel engine in a DF mode with gasoline port injection increased HRR and BTE on account of lower fuel. There is a noticeable change in reduction of BSFC by increasing the gasoline fraction (Vipavanich *et al.*, 2018). It was found that at lower CR, the engine delivered better performance and lesser emissions. But, there was a slight increment in the fuel consumption (Ren *et al.*, 2018). The engine is tested for different ranges of speed and torque with gasoline ratio at 66%. It was reported that the engine shows better performance. Exhaust gas temperature was lower that reduced NO_x emissions to a reasonable level (Xu *et al.*, 2018). Biogas and NG were used with diesel in different compositions. The injection of the gaseous fuels took place in the intake manifold for mixing with air. For simulating the HRR single zone model coupled with a double Wiebe function was followed. The experimental data obtained was utilized to calibrate and validate the predictive model (Aklouche *et al.*, 2018). A biogas run DF diesel engine is used for the tests. For higher equivalence ratio, the BTE of the engine reduced drastically and addressed by preheating the gas that resulted in increment of BTE by almost 5%. Diesel-like trends of BTE were achieved at low equivalence ratio and preheating (Sarkar and Saha, 2018). One-dimensional and three-dimensional computational fluid dynamics (CFD) models were built and validated on the basis of test results. Advancing the injection angle resulted in maximum in-cylinder pressure and HRR; besides, they were close to TDC on *P*–*θ* diagram. When the start of combustion (SOC) was after TDC, BTE improved with the increase of APID and vice versa was reported (Shu *et al.*, 2018). A study of variation of NG flow rate from 0 to 75% at a constant air and diesel consumption rate on six-cylinder turbocharged intercooler DF engine at 1,355 rpm and 25% load condition, the engine parameters such as in-cylinder pressure and HRR reported and HRR curve changes from

single peak to two peaks, and there is a clear difference between the two peaks. At 10% load condition, the combustion was like homogeneous charge compression ignition (HCCI) mode of engine operation (Wang *et al.*, 2018). The engine runs with four different ethyl glycol (EG) energy ratios, that is, EG0, EG5, EG10 and, EG15. Use of EG in fumigation mode showed increase in the cylinder PP and HRR. Also, BTE of the engine enhanced on account of shortened combustion duration (CD). A slight increase in BSFC was also reported (Chen *et al.*, 2018). H₂ has a higher ignition temperature, which allows the engine to function at greater CR desired for diesel engines (Saravanan *et al.*, 2007). The diesel engines fueled with H₂-diesel in DF mode resulted in improved BTE besides reduction in smoke, CO₂, and CO. However, there was no change in NO_x formations (Saravanan and Nagarajan, 2010; Srinivasan and Subramanian, 2015). There are few studies carried out on CRDi engines by different strategies and using different combination of fuels (Duda *et al.*, 2018; Roy *et al.*, 2014; Kim and Choi, 2010; Ashok *et al.*, 2018). However, to the best of authors' knowledge, it can be concluded that the combined effect of HFR, IP and EGR on the performance of CRDi engine fueled with H₂ and BCPO has not been studied.

Therefore, the current research is an effort to study and evaluate the performance of CRDi engine in DF mode with diesel-H₂ and BCPO-H₂ fuel combinations with TRCC.

2. Experimental details

2.1 Fuels used

In the present work, H₂ was supplied along with air while suction stroke and diesel/BCPO were used as pilot fuel. The flow rate of hydrogen was controlled by a flow control valve placed in the fuel flow line before mass flow meter. The flow control valve lever was rotated till the required flow ensures in mass flow meter. Beyond 0.22 Kg/h of hydrogen supplied, knocking was observed. The physicochemical properties of diesel and BCPO are shown in Table 1

Ceiba pentandra belongs to the Malvaceae family. It is a nonedible oil. This is abundantly available in India and other Asian countries. The seeds of *Ceiba pentandra* contain about 28–30% oil. It contains high fiber and can be used for ethanol production. The physicochemical and fatty acid composition of *Ceiba pentandra* and its effect on the biodiesel production were investigated by several investigators (Silitonga *et al.*, 2013; Yunus Khan *et al.*, 2015), and performance study on diesel engine powered with *Ceiba pentandra* was carried out by Nagesh *et al.* (2017). BPCO has properties similar to diesel fuel.

2.2 Experimental setup

The engine tests were carried out on single-cylinder water-cooled four-stroke diesel engine. The specifications of diesel engine are provided in Table 2.

S. No	Properties	Diesel	BCPO
1	Viscosity (cSt at 40 °C)	2.5	4.3
2	Flash point (°C)	65	202.5
3	Calorific value (kJ/kg)	45000	39790
4	Density (kg/m ³ at 15 °C)	830	884.4
5	Cetane number	45–55	42.4
6	Cloud point (°C)	–2	3
7	Pour point (°C)	–5	5
8	Carbon residue (%)	0.1	0.06
9	Type of oil	Fossil fuel	Nonedible

Table 1.
Properties of diesel
and BCPO

HFR varied from 0.1 to 0.22 kg/h and maximum substitution possible was 0.22 Kg/h for smooth operations at CR of 17.5 and constant speed of 1,500 rpm. The flow rate of hydrogen was controlled by a flow control valve placed in the fuel flow line before mass flow meter. The flow control valve lever was rotated till the required flow ensures in mass flow meter. The combined effects of HFR and IP and EGR on CRDi engine run in DF mode with BCPO-H₂ combination were investigated. Engine was cooled by circulating water through the jackets of engine block and cylinder head. In-cylinder gas pressure was measured with piezoelectric pressure pickup, which has a sensitivity of 0.145 mV/kPa. The specifications of pressure pickup are given in Table 3.

Engine-Soft software data control was used to monitor the engine operating conditions. All the combustion and performance parameters were measured and recorded for various loading conditions. The results are based on the average value of three tests conducted for each fuel to obtain more accurate and reliable data.

HRR at each CA was calculated from 100 cycles with first law analysis using Eqn (1).

$$Q_{app} = \left(\frac{\gamma}{\gamma - 1} \right) p \cdot dv + \left(\frac{1}{\gamma - 1} \right) v \cdot dp + Q_{wall} \quad (1)$$

Where,

Q_{app} – Apparent heat release rate (J)

γ – Ratio of specific heats $C_p / (C_p - \bar{R})$

R – Gas constant in (J / kmol·K)

C_p – Specific heat at constant pressure (J / kmol – K)

V – Instantaneous volume of the cylinder (m³)

P – Cylinder pressure (bar)

Q_{wall} – Heat transfer to the wall (J)

Sl No	Parameter	Specifications
1	Fuel injection pressure	200–225 bar
2	No. of cylinders	One
3	No. of strokes	4-S
4	Fuel	High-speed diesel
5	Rated power	5.2 kW (7 HP at 1500 RPM)
6	Bore diameter	0.0875 m
7	Length of stroke	0.11 m
8	Compression ratio	17.5: 1

Table 2.
Specifications of CI
engine

Sl No	Parameter	Specifications
1	Make	PCB Piezotronics
2	Model	HSM111A22, Piezoelectric
3	Measurement range	0–344 bar
4	Sensitivity	0.145 mV/kPa
5	Resolution	0.69 kPa
6	Nonlinearity	≤2.0 % FS
7	Temperature range	–73 to 135 °C

Table 3.
Specifications of
pressure pickup

For this calculation, cylinder gas was assumed to behave as an ideal gas (air) with specific heat being dependent on temperature (Hayes *et al.*, 1986). The specific heat was found using Eqn (2).

$$C_p = \left[3.6359 - \frac{1.33736T}{1000} + \frac{3.29421T^2}{1 \times 10^6} - \frac{-1.91142T^3}{1 \times 10^9} + \frac{0.27542T^4}{1 \times 10^{12}} \right] R \quad (2)$$

for $T < 1000$ K

$$C_p = \left[3.04473 + \frac{1.338056T}{1000} - \frac{0.488256T^2}{1 \times 10^6} + \frac{0.0855475T^3}{1 \times 10^9} - \frac{0.00570127T^4}{1 \times 10^{12}} \right] R \quad (3)$$

for $T > 1000$ K

Heat transferred to the wall was determined with the Hohenberg Eqn (4) (Hohenberg, 1979) and assuming the wall temperature to be 723 (Hayes *et al.*, 1986).

$$Q_{\text{wall}} = h \times A \times [T_g - T_w] \quad (4)$$

where

$$h = C_1 V^{-0.06} P^{0.8} T^{-0.4} (V_p + C_2)^{0.8} \quad (5)$$

h – Heat transfer coefficient in $\text{W/m}^2 \text{K}$

C_1 and C_2 – Constants, 130 and 1.4

V – Cylinder volume in m^3

P – Cylinder pressure in bar

T – Cylinder gas temperature in K

V_p – Piston mean speed in m/s

A – Instantaneous Area (m^2)

3. Results and discussions

3.1 Effect of HFR on the performance of CRDi engine

The effect of different HFR on CRDi engine with DF mode is discussed in this section. CI engine was operated with diesel, keeping the fuel IT of 23° bTDC and IOP of 205 bar with normal combustion chamber. Toroidal re-entrant combustion chamber (TRCC) was used during CRDi mode of engine operation. These readings were used for the comparison of results of CRDi engine in DF mode with fuel combinations selected. Liquid fuel IT of 10° bTDC was maintained for diesel/BCPO injection during CRDi engine operation.

3.1.1 Brake thermal efficiency. The variation of BTE with different HFR and engine loads (brake power) for diesel engine with CRDi facilities and CI mode has been shown in Figure 1. From graph, at all engine loads BTE increases with increase in HFR. The reason could be better combustion on account of higher cylinder temperature resulted due to fast burning speed of H_2 . Higher PP and HRR with lower combustion duration shown in Figures 10–12 could also be the reason for the trend. Better combustion qualities of diesel fuel showed better performance as compared to BCPO at all loads. CRDi engine with BCPO gave 13.6% lower BTE as compared to CI mode with diesel at CR of 17.5 and HFR of 0.22 Kg/h at 80% load.

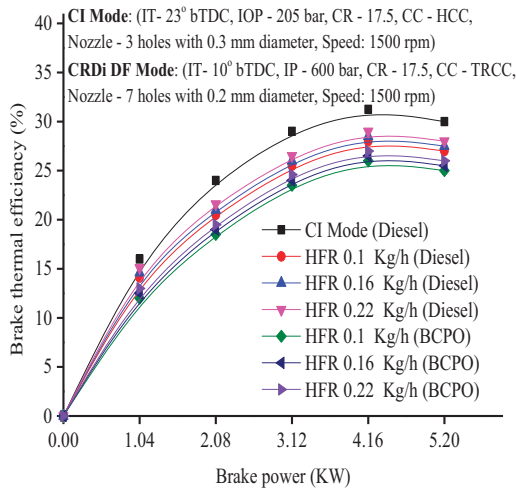


Figure 1.
Effect of HFR and BP on BTE of CRDi engine

3.1.2 HC and CO emissions. Figure 2a and b represent the variations in HC and CO emissions with variations in HFR and BP respectively for CRDi engine. It can be observed that induction of H_2 in CRDi engine with diesel as well as BCPO resulted in lesser amounts of HC and CO at various engine loads. This reduction in HC and CO is attributed to low carbon in the fuel mixture. Faster combustion of mixture could also be the reason for the trend observed. CRDi engine resulted in same HC emission at CR of 17.5 and HFR of 0.22 Kg/h at 80% load in comparison with CI mode, but 5.4% lower CO was revealed with same operating conditions. Similar results were revealed in literature (Tsujiyura and Suzuki, 2017; Verma *et al.*, 2018).

3.1.3 NO_x emissions. Figure 3 shows the effect of HFR on NO_x emissions of CRDi engine in DF mode. NO_x emission elevated with HFR at all loads in DF mode of CRDi engine operation. The simple reason could be lower ID and higher HRR that increased combustion temperature due to higher flame speed of H_2 . BCPO showed lower NO_x than diesel fuel at all loads due to slightly higher ID and higher HRR observed for BCPO. CRDi engine NO_x was 25.6% lower with BCPO at HFR of 0.22 Kg/h and CR of 17.5 at 80% load as compared to conventional CI mode. Similar results were reported in literature of Li *et al.* (2018).

3.2 Effect of variations in fuel IP on the performance of CRDi engine

This section highlights the effect of variations in fuel IP on the performance of CRDi engine run DF mode. During experimentation, HFR of 0.22 Kg/h was maintained constant and fuel IP varied from 800 bar to 1,000 bar.

3.2.1 Brake thermal efficiency. Effect of fuel IP on BTE of CRDi engine is provided in Figure 4. BTE was higher at 900 bar IP at all loads, but it slightly decreased at maximum IP. Enhanced air fuel mixing due to better atomization and more penetration distance at higher IP and lower ID could be the reason. But at maximum IP BTE decrease could be because of increased wall wetting. H_2 -diesel operation gave slightly higher BTE as compared to H_2 -BCPO. This could be due to better combustion qualities of diesel. CRDi engine showed about 10.4% lower BTE with BCPO at IP of 900 bar and HFR of 0.22 Kg/h without knocking. Similar results were observed in literature (Lee and Park, 2002; Leung *et al.*, 2006).

3.2.2 HC and CO emissions. HC and CO emissions with IP and BP are illustrated in Figure 5 respectively. CRDi engine in DF mode showed increase in HC and CO emission with load, which is obvious due to more liquid fuel injected. Lower HC and CO were observed for 900 bar IP due to better combustion due to more homogeneous mixture formed and shorter ID

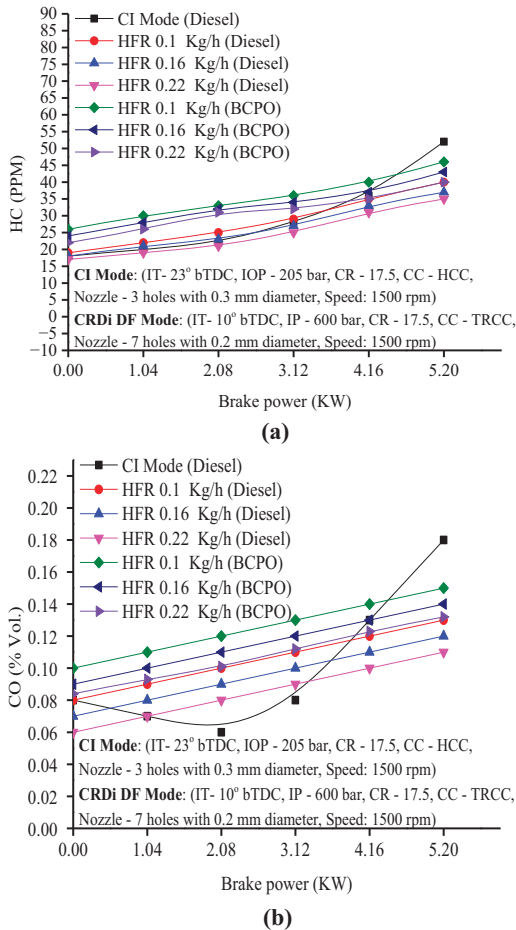


Figure 2.
Effect of HFR and BP
on (a) HC and (b) CO of
CRDi engine

due to higher combustion temperature. H_2 fuel has higher flame speed that reaches the CC wall in less time; this led to complete combustion, which resulted in lower HC and CO emissions. Similar results were reported in literature [Verma et al. \(2018\)](#). At 80% load, CRDi engine showed about 11% lower HC and 15.4% lower CO with BCPO at HFR of 0.22 Kg/h and IP of 900 bar as compared CI mode with diesel.

3.2.3 NO_x emissions. NO_x emission of CRDi engine in DF mode with IP and BP is presented in [Figure 6](#) NO_x emission level in the engine exhaust is mainly due to the nitrogen content in the air. The increase in NO_x emission was seen with increase in IP. Higher cylinder gas temperature and higher pressure in combustion chamber because of quick burn rate of H_2 with higher HRR could be the reason for higher NO_x emission. CRDi engine revealed 24.2% lower NO_x with BCPO at HFR of 0.22 Kg/h at 80% load. Similar results were reported in literature [\(Kumar et al., 2018\)](#).

3.3 Effect of EGR on performance of CRDi engine in DF mode

To reduce the NO_x emission of CRDi engine, EGR was used in different percentages. The effect of EGR percentage on the performance of CRDi engine is provided in this section.

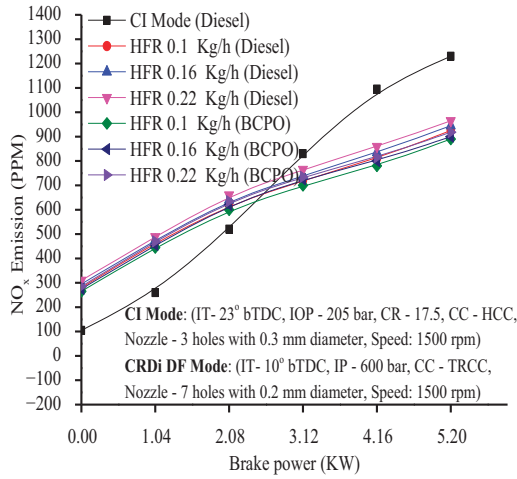


Figure 3. Effect of HFR and BP on NOx of CRDi engine

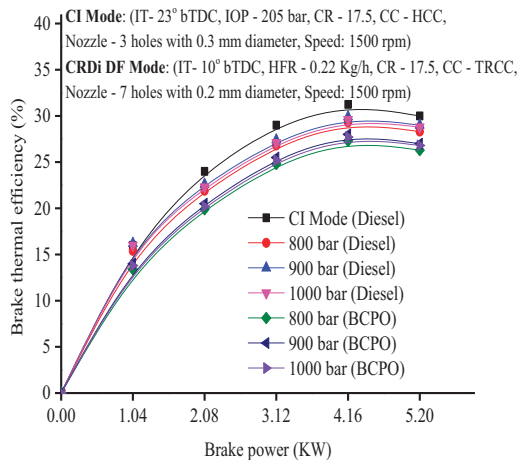


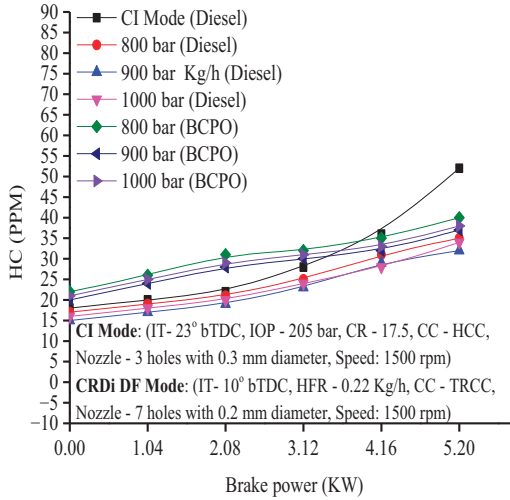
Figure 4. Effect of IP and BP on BTE of CRDi engine

Maximum HFR of 0.22 Kg/h was maintained with fuel IP of 900 bar during the experimentation.

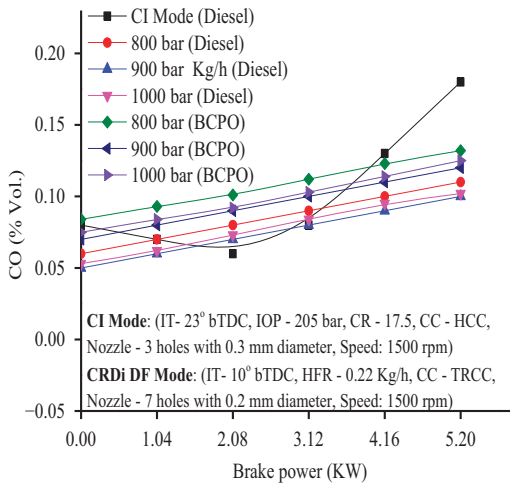
3.3.1 Performance: brake thermal efficiency. Figure 7 shows the effect of EGR on BTE of CRDi engine. Decrease in BTE was observed with increase in EGR at all loads. The reason might be dilution effect of the charge. CRDi engine yielded 12.6% lower BTE with BCPO at HFR of 0.22 Kg/h, IP of 900 bar and 15% EGR at 80% load.

3.3.2 HC and CO emissions. Figure 8 depicts the effect of EGR on HC and CO emissions of CRDi engine respectively. HC and CO emissions were higher at 20% EGR as compared to other EGR used due to increased ID and lower HRR. CRDi engine showed about 5.5% lower HC and 7.7% lower CO with BCPOs as compared to CI mode at HFR of 0.22 Kg/h, IP of 900 bar and EGR of 15% at 80% load.

3.3.3 NO_x emissions. NO_x emission with EGR and BP is provided in Figure 9. CRDi engine operation in DF mode with H₂ yielded higher NO_x at higher loads as compared to lower loads.



(a)



(b)

Figure 5.
Effect of IP and BP on
(a) HC and (b) CO of
CRDi engine

Fast burning of H_2 fuel enhanced the combustion of mixture due to lower ID, which increased the combustion temperature that resulted in higher NO_x .

At EGR of 20%, NO_x emission was much lower but BTE reduced significantly. EGR of 15% could be the better choice to reduce the NO_x emission with little compromise in BTE. CRDi engine showed about 26% lower NO_x with BCPO as compared to CI mode with IP of 900 bar, HFR of 0.22 Kg/h and EGR of 15% at 80% load. CRDi engine operation with diesel- H_2 showed slightly higher NO_x as compared to BCPO- H_2 due to better combustion qualities. Similar trends were reported in literature (Kumar *et al.*, 2018; Tarabet *et al.*, 2018).

3.3.4 Combustion duration (CD). The changes in CD is provided in Figure 10, and CD was calculated with time duration between SOC and 90% cumulative amount of heat release.

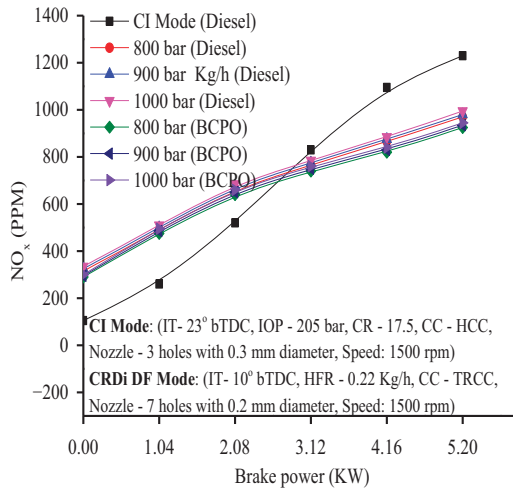


Figure 6. Effect of IP and BP on NO_x of CRDi engine

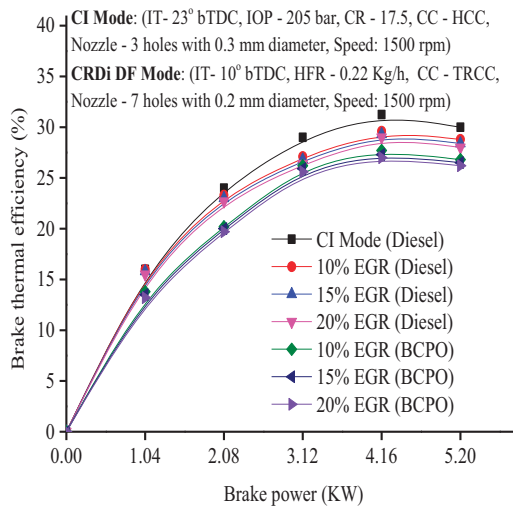
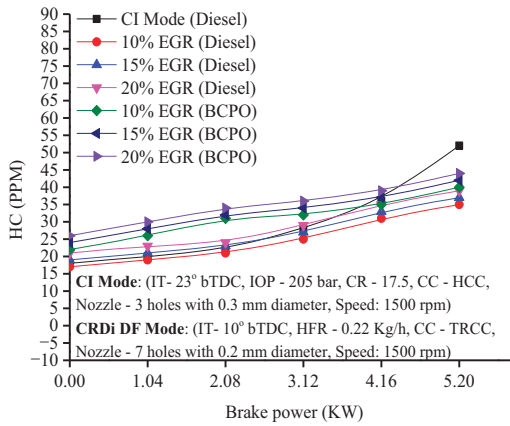


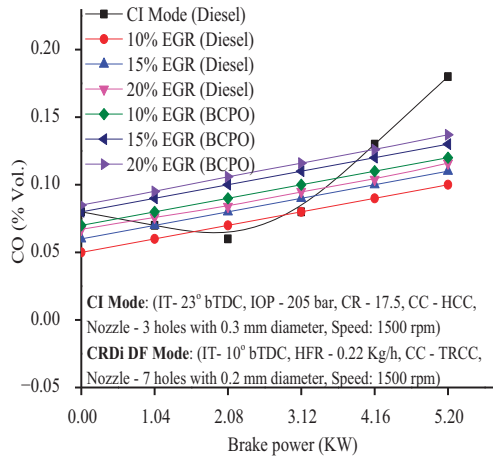
Figure 7. Effect of EGR and BP on BTE of CRDi engine

CD increased with load. Lower CD was observed for hydrogen addition as compared to diesel-only operation and higher proportion of hydrogen also showed lower CD. It might be because of its higher burning velocity, which made the mixture to burn fast. However, CD was little more with BPCO due to its higher viscosity. Similar results were reported in literature (Dhole *et al.*, 2016; Tarabet *et al.*, 2018).

3.3.5 Peak pressure (PP) and heat release rate (HRR). Figure 11 gives the effect of EGR and BP on PP. The PP depends on the combustion velocity and total amount of fuel burnt in rapid combustion time period. Higher PP was observed with load. Faster burning rate of mixture could be responsible for higher PP and slightly higher adiabatic flame temperature. Figure 12 illustrates HRR with BP of the CRDi engine. During experimentation, increasing trend of HRR with BP was observed because of more fuel requirement at higher load. Better air-fuel



(a)



(b)

Figure 8.
Effect of EGR and BP on (a) HC and (b) CO of CRDi engine

mixture led to better combustion, which could also be the reason for the higher HRR. Similar results were reported in literature (Dhole *et al.*, 2016; Tarabet *et al.*, 2018).

4. Conclusions

This work analyzed the performance of CRDi engine operated on diesel/BCPO and H₂ combination with different HFR, IP and EGR. The experimental work carried out on CRDi engine in DF mode reveals the following conclusions:

- (1) Inducting H₂ fuel at 0.22 kg/h saved liquid pilot fuel up to 65%. CRDi engine operation with HFR of 0.22 kg/h, IP of 900 bar and TRCC shape resulted in better performance and lower emission levels.
- (2) CRDi operation resulted in about 10.4% lower BTE at CR of 17.5, HFR of 0.22 kg/h and TRCC shape as compared to CI mode with diesel.

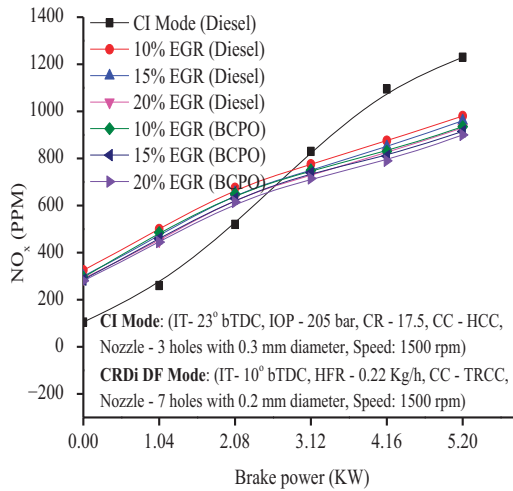


Figure 9.
Effect of EGR and BP
on NO_x of CRDi engine

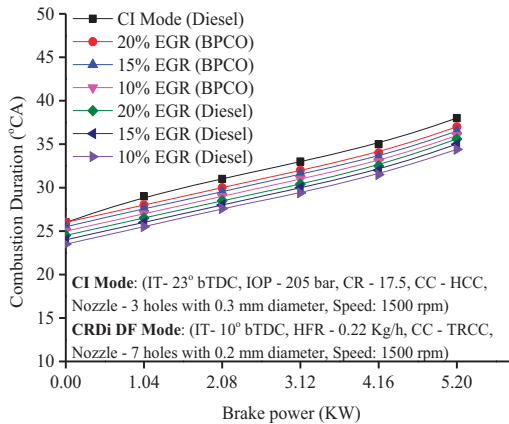


Figure 10.
Effect of EGR and BP
on Combustion
Duration of CRDi
engine

- (3) CRDi operation resulted in 16.7% lower HC emission and 15.4% lower CO emission at optimum conditions for 80% load as compared to the CI mode.
- (4) CRDi engine resulted in 24.2% lower NO_x emission at 80% load as compared to the CI mode.
- (5) With EGR of 15%, CRDi engine revealed 12.6% lower BTE, 5.5% lower HC, 7.7% lower CO, 26% lower NO_x at 80% load as compared to the CI mode.
- (6) CRDi engine showed 2.6% lower CD, 3.4% higher PP and 4.3% higher HRR at 80% load as compared to the CI mode.

Overall, it could be concluded that the CRDi engine operation in DF mode was smooth with diesel/BCPO and H₂. CRDi engine operation with these fuel combinations resulted in complete freedom from fossil diesel besides addressing the energy security of the nation.

Figure 11.
Effect of EGR and BP
on Peak Pressure of
CRDi engine

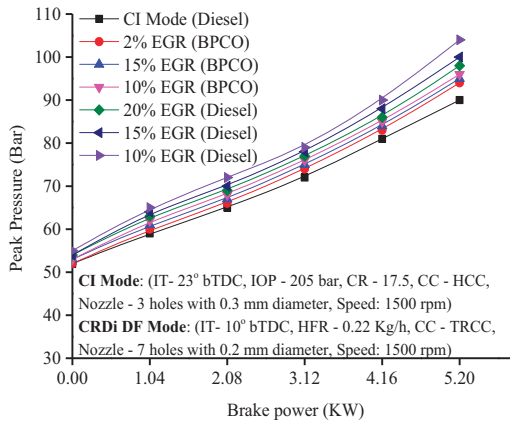
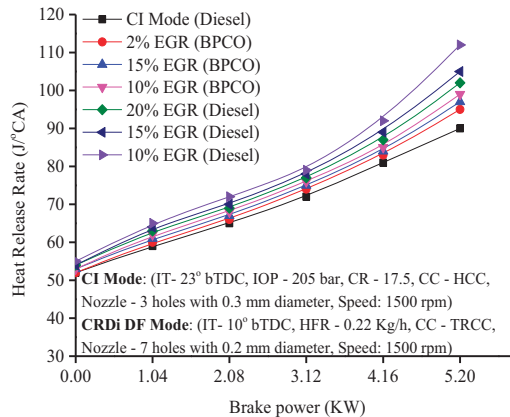


Figure 12.
Effect of EGR and BP
on Heat Release rate of
CRDi engine



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