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Effect of injection timing on the performance of CRDI diesel engine fuelled with fish oil biodiesel and its blends doped with pyrogallol antioxidants

In the present study an experimental work has been conducted to characterize the fish oil biodiesel and their blends with diesel and Pyrogallol antioxidant respectively. Fish oil biodiesel (FHOBD) is blended with diesel to produce FHOBD B20. Further to study the effect of antioxidant addition to FHOBD B20, three blends with varied dosage of pyrogallol are prepared. Accordingly, FHOBD B20 is infused with 1, 2, and 3 grams of pyrogallol antioxidant per liter to produce FHOBD B20PG1, FHOBD B20PG2 and FHOBD B20PG3 respectively. Beyond 3 gm deterioration in the blend homogeneity is observed. For the CRDI engine performance evaluation only FHOBD B20PG3 is considered. Advancing the injection timing to 17º BTDC resulted into improved CRDI engine performance powered with fish oil biodiesel. Further adding Pyrogallol antioxidant into FHOBD B20 blends higher BTE, lower emissions of smoke, HC and CO emissions were obtained for the CRDI engine respectively.

Keywords: Fish oil biodiesel, pyrogallol, antioxidant, CRDI, injection timing.

1.0 Introduction

Diesel engines have variety of applications due to their higher BTE and they are rougher than gasoline fuelled engines. In the present scenario the conventional fuels may deplete within a span of 10-15 years, due to larger demand of energy. Due to amplified usage of imported products of petroleum results into foreign exchange growth and put load on the economy of the country. Further, strict environmental guidelines increased the demand for partial or complete replacement of conventional fuels with the usage of biodiesels [1]. Biodiesel prepared from waste fish oil could be the very attractive and less costly alternate fuel for diesel. Fish processing industries produces large amount of fish tissue waste and other by-products. These fish waste and other by-products are either rejected or vended at low cost for compost or animal feeds [2]. A superior way to use these by-products is to transform into biodiesel for the benefit of diesel engines. India had one of the elongated coastal regions in Asia and it had outstanding potential in case of fish and by-products of fish containing fish oil and fish meal. The biodiesel produced from locally available fish oil had ability to provide sustainable supply of energy by using this fuel in diesel engines. Fish oil biodiesel also helpful in cost savings and to reduce the dependency on fossil fuels [3]. Clean combustion and easy manufacturing of fish oil methyl ester could be the potential way to reduce requirements of diesel in India [4]. The oxidation stability in case of various alternative fuels may be affected by the existence of unsaturated fatty acids and presence of unwanted impurities and absence of naturally existing antioxidants in the biodiesel feedstock [5]. Nishant et al. (2020) [6] found that, by infusing 950 ppm of pyrogallol antioxidant the biodiesel obtained from Alexandrian laurel could be gathered over extended time period. Avase et al. (2015) [7] found that, for 50% load the BTE and BSFC for the engine running with waste cooking oil biodiesel blend B20A were found to be 0.12% and 0.0295% higher than diesel. CO_2 and NO_2 emissions for B20A were found to be 3.64% and 0.31% higher, while CO and HC were 16.67% and 2.33% lower compared to diesel. Dwivedi and Sharma (2015) [8] used pyrogallol antioxidant in pongamia biodiesel as per the observation enhancement in the stability characteristics of pongamia biodiesel is reported. The optimized quantity of pyrogallol antioxidant for blend PB20 was 300 ppm. Waweru

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et al. (2019) [9] found that, blends of clove with pyrogallol antioxidant exhibited much better improvements in oxidation stability about 398% at 800 ppm also babul with pyrogallol antioxidant resulted decrement in performance about 46%. Kivevele et al. (2011) [10] found that, out of three antioxidants studied pyragollol and propyl gallate were more effective antioxidants compared to butylated hydroxyanisole in all infuse ranges. Only 200 ppm of both pyragollol and propyl gallate was able to fulfill the minimum condition of oxidation stability.

From the exhaustive literature survey, it is found that the work on CRDI engines powered with fish oil biodiesel is less reported. Further effect of IT, IOP and NG on the CRDI engine fuelled with fish biodiesel and its blends with antioxidants and their utilization in CRDI engines is scantily reported.

Hence the objectives of this study is to characterize the fish oil biodiesel and their blends with diesel and pyrogallol antioxidant respectively. Fish oil biodiesel (FHOBD) is blended with diesel to produce FHOBD B20. Further to study the effect of antioxidant addition to FHOBD B20, three blends with varied dosage of pyrogallol are prepared. Accordingly, FHOBD B20 is infused with 1, 2, and 3 grams of pyrogallol antioxidant per liter to produce FHOBD B20PG1, FHOBD B20PG2 and FHOBD B20PG3 respectively. Beyond 3 gm deterioration in the blend homogeneity is observed. For the CRDI engine performance evaluation only FHOBD B20PG3 is considered. The second objective is to evaluate the performance of CRDI engine powered with diesel, FHOBD, FHOBD B20 and FHOBD B20PG3 respectively with varied IT, IOP and NG respectively.

Fig.1: Set up for BDF production

TABLE 1: FATTY ACID COMPOSITIONS OF FISH OIL

Fatty acids	Fish oil, vol%
Palmitic C16:0	12.5
Stearic C18:0	6.6
Oleic C18:1	28.9
Linoleic C18:2	35.5
Linoleic C18:3	16.5

TABLE 2: PROPERTIES OF DIESEL, FISH OIL, BIODIESEL AND ITS BLENDS WITH DIESEL

	Properties	Diesel	Fish oil	FHOBD B100	FHOBD B20	FHOBD B20PG3
01	Chemical Formula (kg/m^3)	$C_{13}H_{24}$	-	-	-	-
02	Density	830	960	883	837	852
03	Calorific Value (kJ/kg)	43,000	36,080	37,180	37,984	38,248
04	Flash Point (^oC)	54	194	167	80	84
05	Cetane Number	45-55	52	56	51	53
06	Kinematic Viscosity mm^2/s	2.3	24.31	4	3.47	3.67
07	Specific Gravity	0.845	0.96	0.883	0.837	0.852
08	Cloud Point (^oC)	-	13	6	-	-
09	Carbon residue (% mass)	-	0.47	-	-	-
10	Type of Oil	Fossil	Edible	Edible	Edible	Edible

2.0 Fuel properties

The physico-chemical properties of the fuels selected profoundly affect the engine performance and emissions levels. Fish oil is edible, and can be used as a viable alternative to diesel. India had one of the elongated coastal regions in Asia and it had outstanding potential in case of fish and by-products of fish containing fish oil and fish meal. The biodiesel produced from locally available fish oil had ability to provide sustainable supply of energy by using this fuel in diesel engines. Fish oil biodiesel also helpful in cost savings and to reduce the dependency on fossil fuels. Clean combustion and easy manufacturing of fish oil methyl ester could be the potential way to reduce requirements of diesel in India. The oxidation stability in case of various alternative fuels may be affected by the existence of unsaturated fatty

Fig.2 Separation of glycerin from BDF and dissolved catalyst removal from BDF

acids and presence of unwanted impurities and absence of naturally existing antioxidants in the biodiesel feedstock.

Table 1 shows the fatty acid compositions of fish oil.

Fish oil biodiesel (FHOBD) is prepared by conventional transesterification. The set up used for biodiesel production is shown in Fig.1.

Table 2 shows the properties of fuels used in the work.

3.0 Experimental Set Up

Experimental set up used for the investigation is shown in Fig.3.

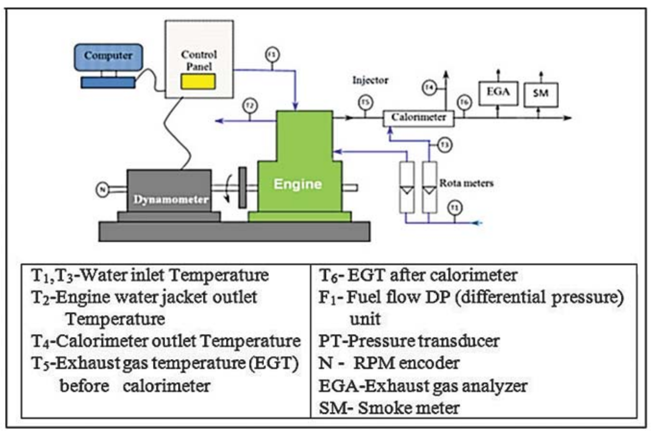

Fig.3 Schematic view of the experimental test rig

Existing diesel engine of 5.2 kW having traditional fuel injection system is suitably modified to operate with high pressure injection system and the engine is operated in CRDI mode. Engine is operated at a constant speed of 1500 rpm. Hemispherical combustion chamber is employed in the engine system. Original conventional injector nozzle having 3 holes each of 0.3 mm is replaced with a 6-hole CRDI injector each having 0.2 mm as shown in Figs.4 and 5.


Fig.4: Conventional injector


Fig.5: CRDI injectors

Figs.6 and 7 show the CRDI engine test rig used in the study with ECU (Electronic Control Unit) facility. At any desirable injection timing as well as injection duration control respectively. Further the pilot fuels can be injected at high opening pressure (IOP) of 600 bar respectively.

Engine specifications are presented in Table 3.

Fig.8 shows the pressure gauge for recording higher fuel injection pressures. The ECU facility in the CRDI engine enables pilot fuel injection.

4.0 Results and discussion

In the present work fuel IT is optimized for CRDI engine fuelled with different fuel combinations.

In order to study the effect of IT on CRDI engine

Fig.6: CRDI system integrated CI engine

Fig.7: ECU facilitated CRDI injectors

Table 3: Specifications of the engine

Make and model	Kirloskar, TV1
Engine type	Single cylinder, four stroke, water cooled, direct injection, diesel engine
Orientation	Vertical
Ignition system	Compression ignition
Bore * stroke	87.5mm * 110mm
Displacement volume	660 cc
Compression ratio	17.5:1
Arrangement of valves	Overhead
Combustion chamber	Open chamber (direct injection)
Rated power	5.2kW (7HP) @1500rpm
Cooling medium	Water cooled
Air measurement manometer	
Made	MX201
Type	U-type
Range	100-0-100mm
Eddy current dynamometer	
Model	AG-10
Type	Eddy
Maximum	7.5kW at 1500-3000rpm
Flow	Water must flow through dynamometer
Dynamometer arm length	0.180meter
Fuel measuring unit range	0.50ml

Fig.8: Pressure gauge for recording fuel IOP

performance IT is varied from 25^{o}CA bTDC to 5^{o}CA aTDC in steps of 5^{o}CA to optimize fuel IT at 80% and100% loads at a constant engine speed of 1500 rpm speed. Pilot fuels are injected at a constant IP of 600 bar by regulating the speed and fuel flow rate of the CRDI pump. A CRDI injector of six holes with each of 0.2 mm is used. It could be noted that the CRDI injector used is well matched to the CI engine combustion chamber (CC) that resulted into smooth engine operation keeping the compression ratio of the engine fixed.

Optimization of IT for CRDI engine operated with selected fuel combinations

4.1 Performance characteristics

Fig.9 depicts the effect of IT on the BTE of CRDI engine fuelled with conventional diesel, FHOBD, and FHOBD B20 respectively for 60%, 80% and 100% loads respectively. Fig.10 depicts the effect of fuel IT on the BTE of CRDI engine fuelled with conventional diesel, FHOBD B20 and FHOBD B20PG3 for 60%, 80% and 100% loads respectively. As the IT is advanced or retarded the BTE of the engine show varied behaviour when powered with different fuel combinations. Biodiesel and their blends with diesel show lower BTE compared to diesel due to their higher viscosity and lower energy content. Diesel show higher BTE when injected at 10^{o}BTDC while the biodiesels and their blends show improved performance when injected with advancing the injection timing of 17^{o}BTDC as shown in Fig.9. Advancing the biodiesel injection at 17^{o}BTDC, higher BTE is obtained due to improved atomization of injected fuel at a fixed IP of 600 bar. Further improved air fuel mixing and reduced wall wetting facilitates improved combustion of the fuels at the respective optimized fuel ITs.

From Fig.10 it follows that difference in the fuel properties due to addition of pyrogallol in FHOBD B20 results into varied BTE behaviour. Adding pyrogallol antioxidant additive in FHOBD B20 i.e., FHOBD B20PG3, higher BTE is obtained due to improved atomization of pilot fuels when injected at 17^{o}BTDC and IP of 600 bar. FHOBD B20 PG3 shows higher BTE compared to FHOBD, FHOBD B20 due to its higher calorific value and lower viscosity as well. Pyrogallol

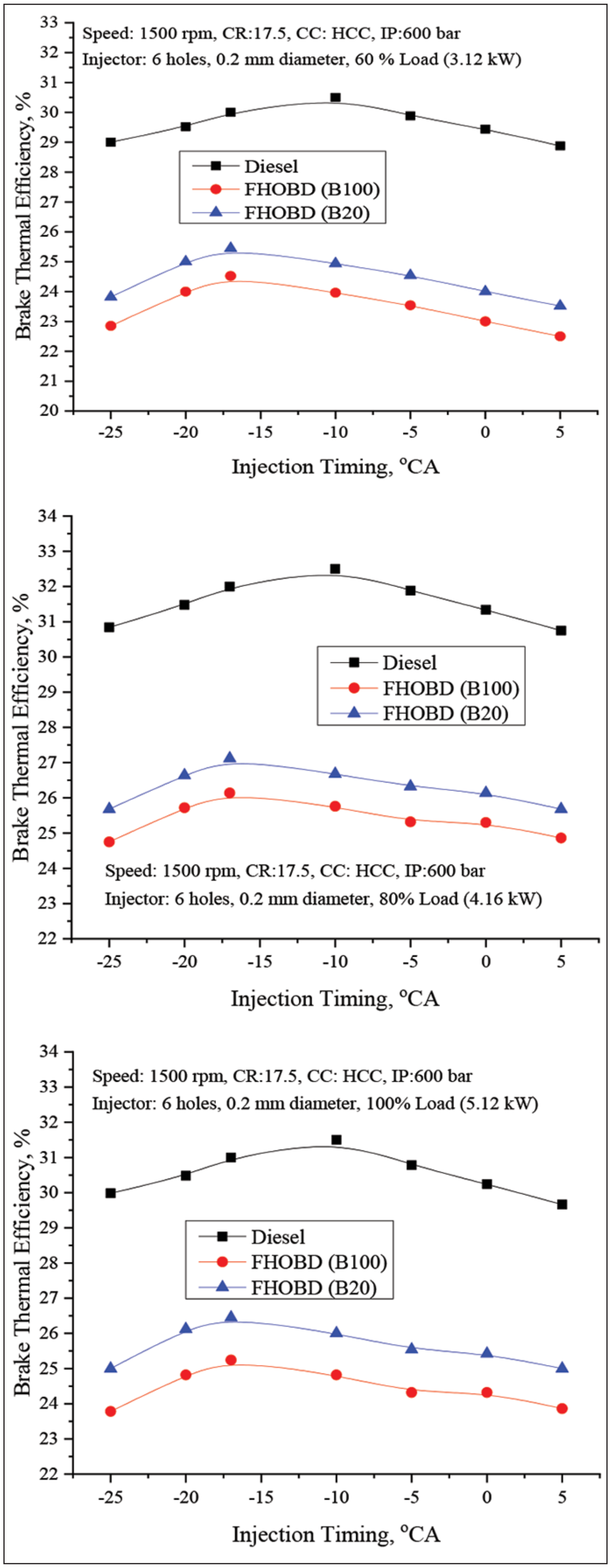

Fig.9: BTE variation with IT at 60%, 80% and 100% loads for FHOBD and FHOBD B20

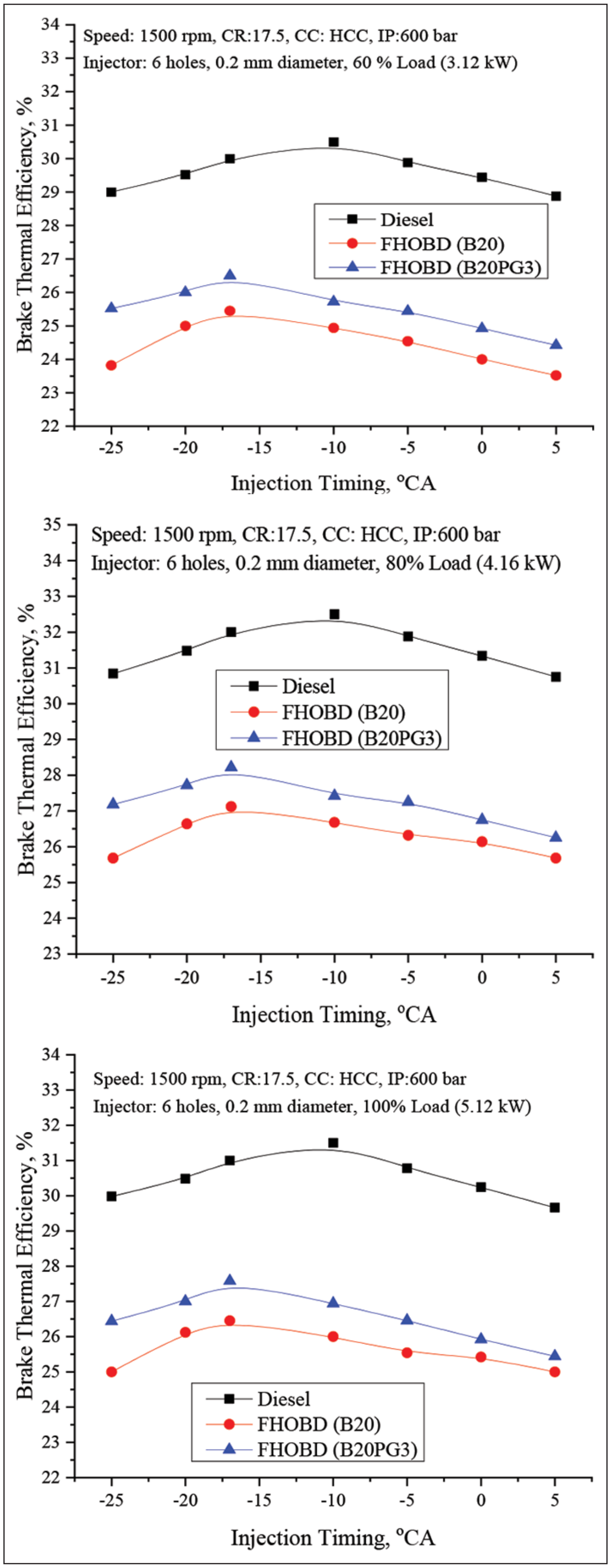

Fig.10 BTE variation with IT at 60%, 80% and 100% loads for FHOBD B20 and FHOBD B20PG3

biodiesel enhanced the oxidation stability of biodiesel and hence BTE is improved with the addition of antioxidant in the fuel.

4.2 Emission characteristics

Smoke emission

Fig.11 depicts the effect of fuel IT on smoke emission of CRDI engine powered with diesel, FHOBD, and FHOBD B20 respectively for 60%, 80% and 100% loads respectively.

Fig.12 depicts the effect of fuel IT on smoke emission of CRDI engine fuelled with diesel, FHOBD B20 and FHOBD B20PG3 for 60%, 80% and 100% loads respectively.

From the figures it may be noted that smoke emissions with biodiesels (BDFs) are higher than diesel. The reasons could be due to higher viscosity of BDFs which provides poor air to fuel mixture occurring inside the engine cylinder. It may be noted that advancing the IT for biodiesel fuel combinations reduces while injecting the diesel closer to TDC reduces the smoke emissions. Diesel shows lower smoke when injected at 10°BTDC while the biodiesels fuelled CRDI engine shows lower smoke with advancing the injection timing of 17°BTDC. Decreasing smoke trends could be due to improved combustion associated with higher BTE as well. Increased trends in the smoke beyond 17°BTDC might be due to higher diffusion combustion phase compared to rapid combustion phase.

From Figs.11 and 12 it follows that for CRDI engine fuelled with FHOBD B20 PG3 shows lower smoke opacity followed by FHOBD B20 and FHOBD B100 respectively due to its comparatively higher calorific value and lower viscosity as well. Pyrogallol biodiesel enhanced the oxidation stability of biodiesel and hence smoke emissions are improved with the addition of antioxidant in the fuel.

HC and CO emissions

Fig.13 to 16 depicts the effect of fuel IT on the HC and CO emissions of CRDI engine fuelled with conventional diesel, FHOBD, FHOBD B20 and FHOBD B20 PG3 for 60%, 80% and 100% loads respectively. Higher HC and CO emissions refer to incomplete combustion occurring inside the engine cylinder. Comparatively higher viscosity of BDFs which result into wall wetting could be the reasons for their higher UBHC emissions. However, advancing the IT for biodiesels lower these emissions compared to injection of diesel closer to TDC. Accordingly, for CRDI engine fuelled with FHOBD B20 and FHOBD B20 PG3, HC and CO emissions are lower at an IT of 17°bTDC, while diesel shows lower emissions at 10° BTDC.

Further optimized quantity of pyrogallol antioxidant additive in FHOBD B20 to stabilize the fuel blends improve the UBHC emissions. At an injection timing of 17°BTDC, FHOBD B20PG3 results into lower HC and CO emissions, due to improved fuel properties and higher BTE at fixed IP of 600

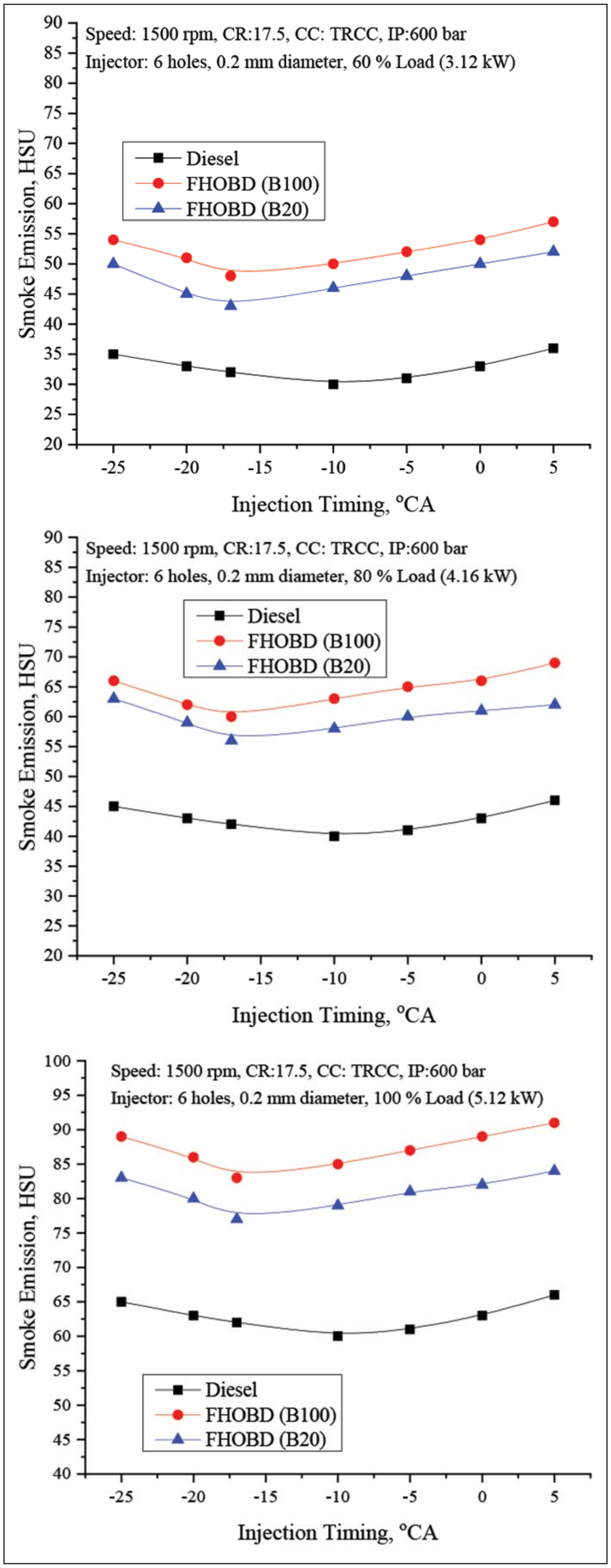

Fig.11: Smoke variation with IT at 60%, 80% and 100% loads for FHOBD and FHOBD B20

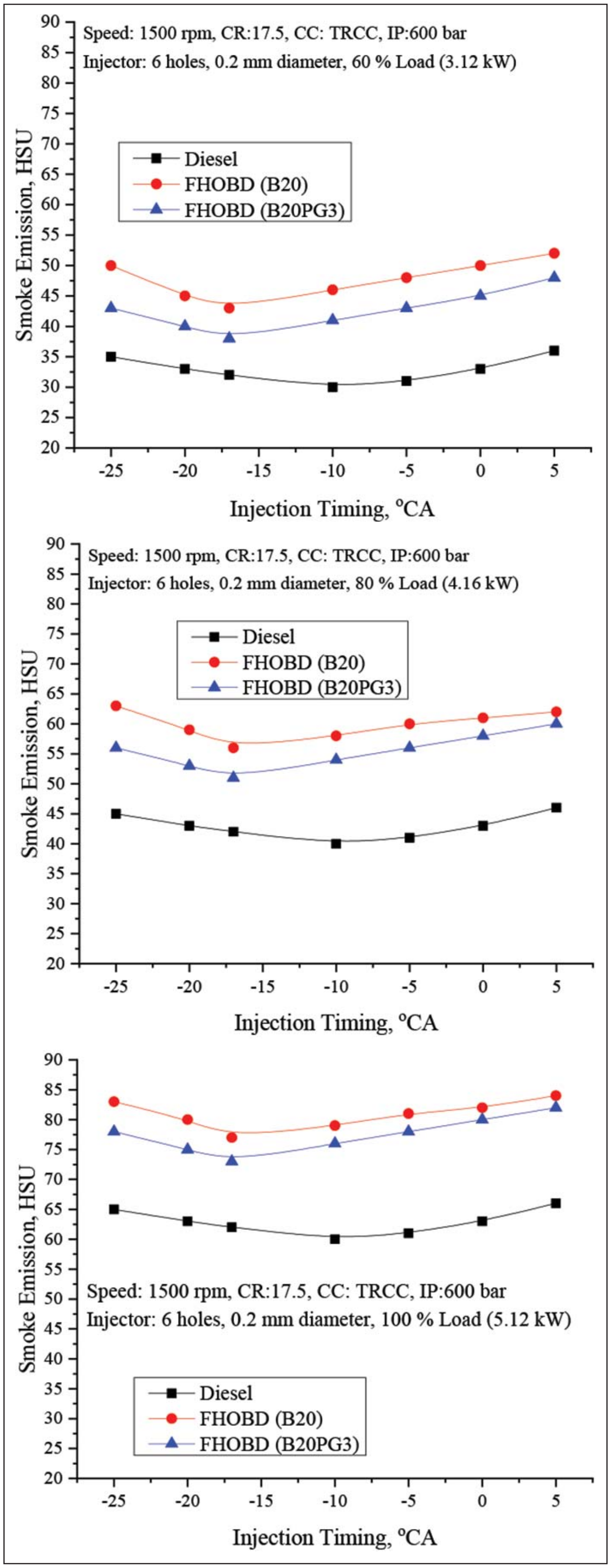

Fig.12: Smoke variation with IT at 60%, 80% and 100% loads for FHOBD B20 and FHOBD B20PG3

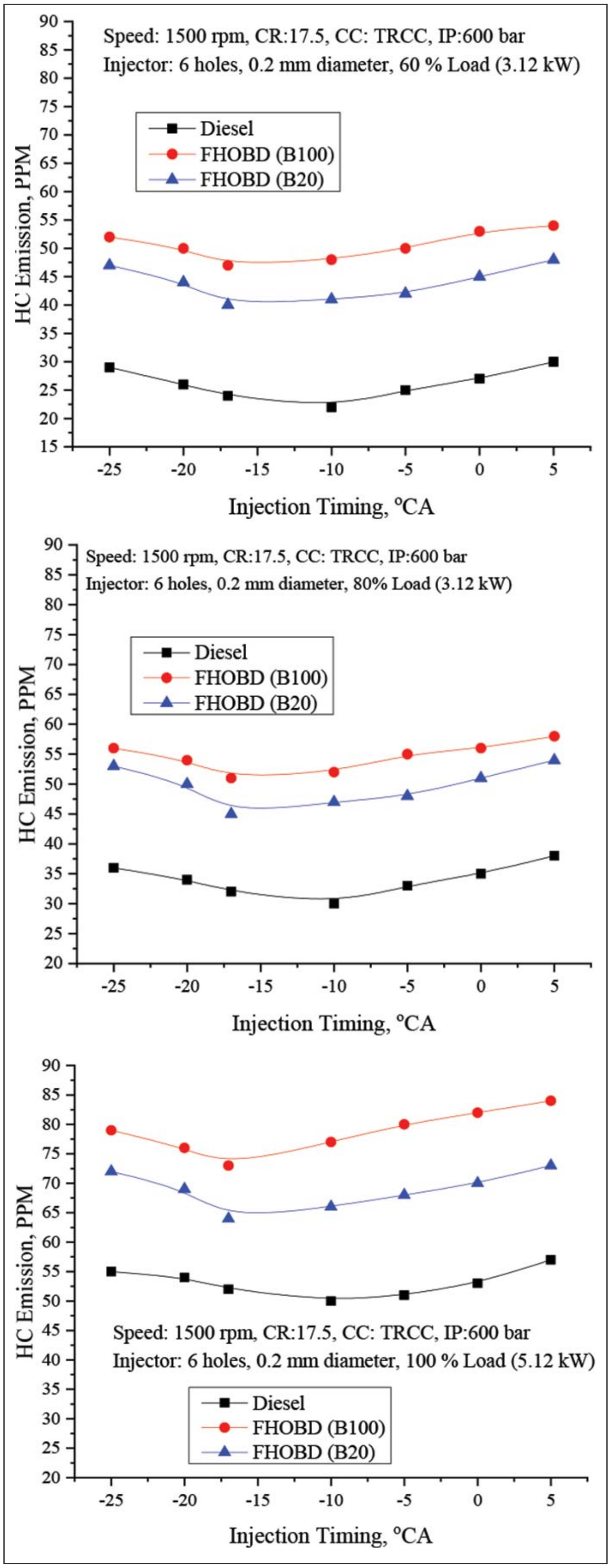

Fig.13: HC emissions variation with IT at 60%, 80% and 100% loads for FHOBD and FHOBD B20

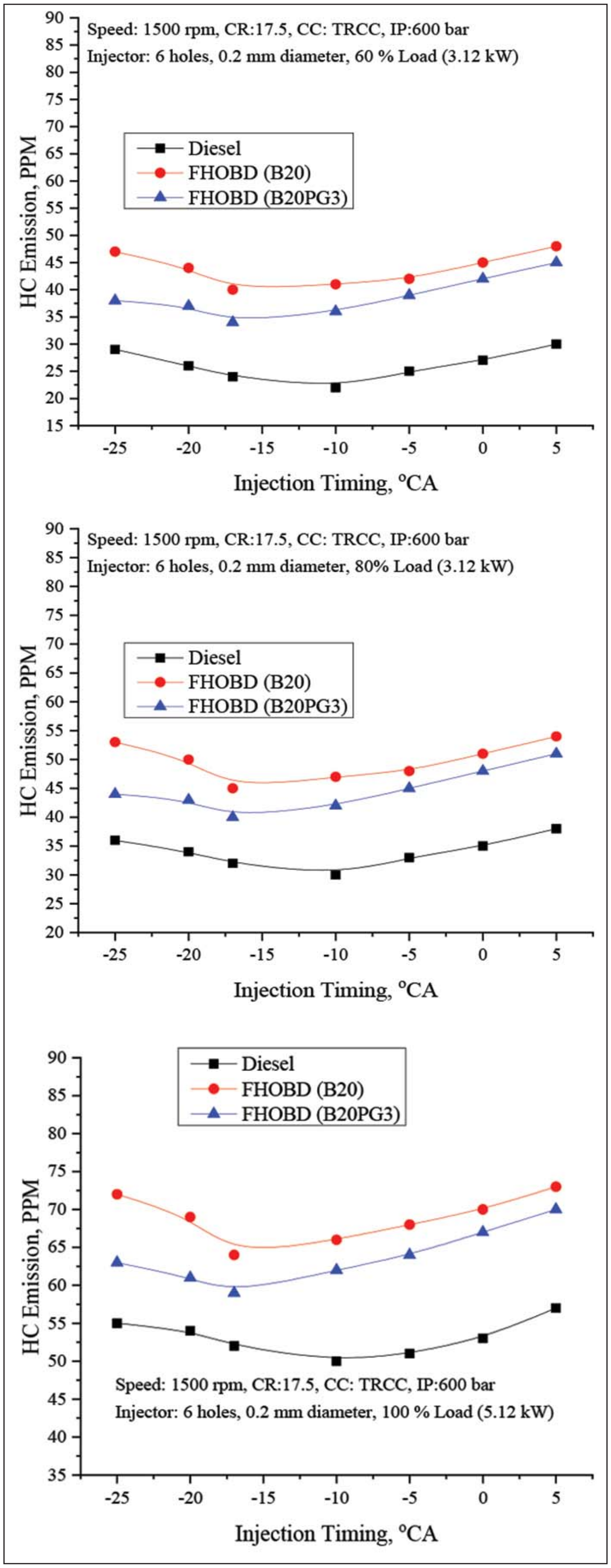

Fig.14: HC emissions variation with IT at 60%, 80% and 100% loads for FHOBD B20 and FHOBD B20PG3

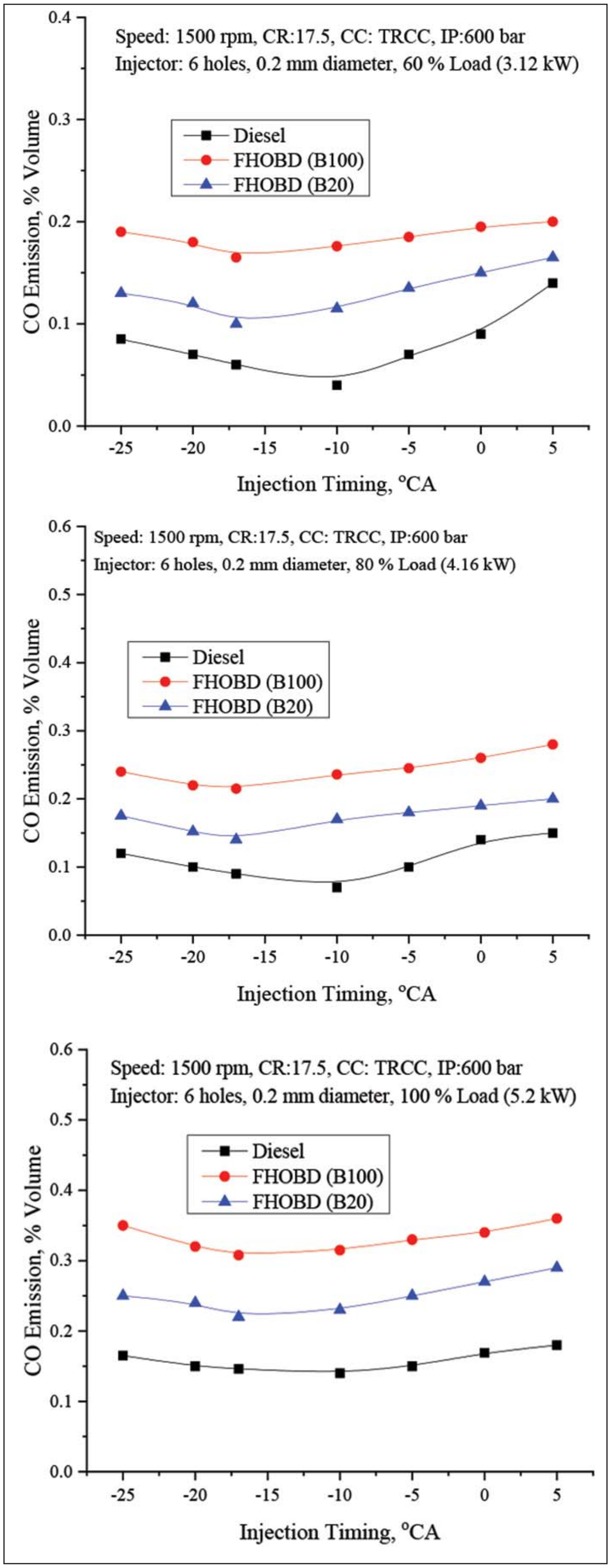

Fig.15 CO emissions variation with IT at 60%, 80% and 100% loads for FHOBD, and FHOBD B20

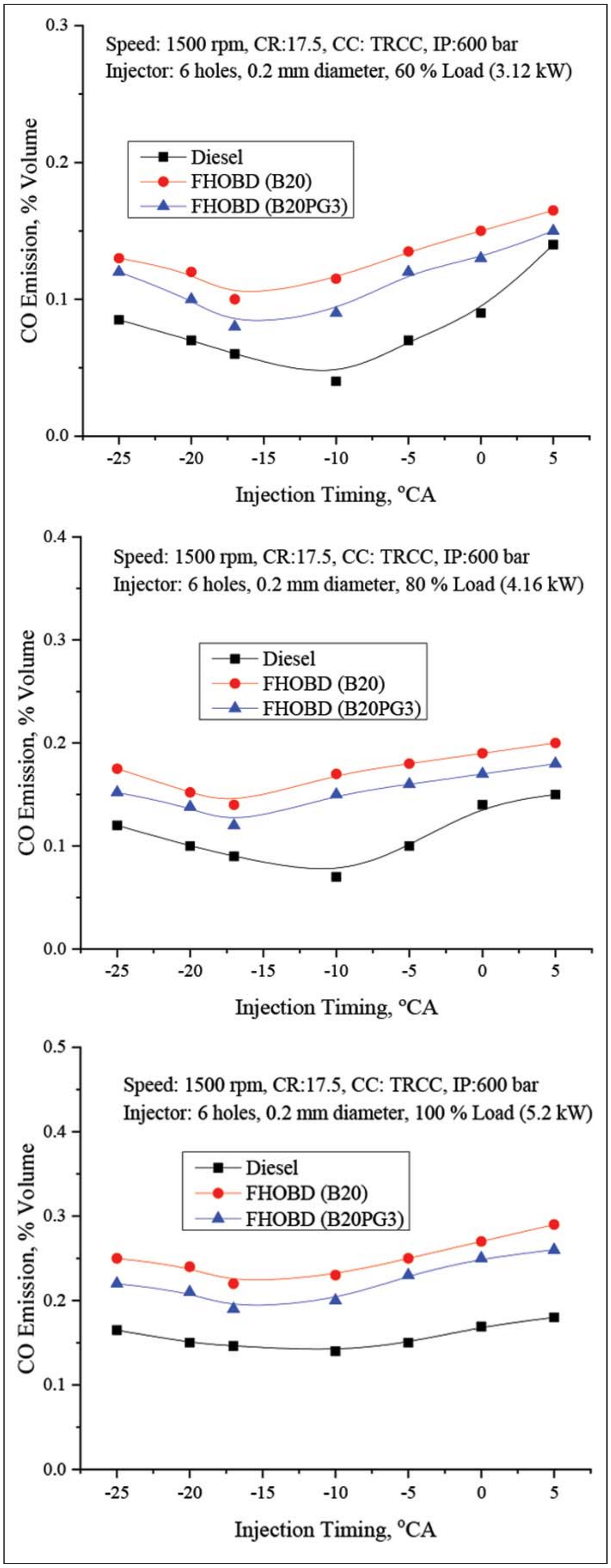

Fig.16 CO emissions variation with IT at 60%, 80% and 100% loads for FHOBD B20 and FHOBD B20PG3

bar. FHOBD B20PG3 shows lower HC and CO emissions compared to FHOBD, FHOBD B20 due to its higher calorific value and lower viscosity as well. Further reduced wall wetting observed with FHOBD B20PG3 compared to FHOBD B20 results into these emission behaviours. Pyrogallol biodiesel enhanced the oxidation stability of biodiesel and hence HC and CO emissions are improved with the addition of antioxidant in the fuel.

NO_x emissions

Fig.17 depicts the effect of fuel IT on NO_x emissions of CRDI engine fuelled with conventional diesel, FHOBD, and it blends with diesel (FHOBD B20) for 60%, 80% and 100% loads respectively.

Fig.18 depicts the effect of fuel IT on the NO_x emissions of CRDI engine fuelled with conventional diesel, FHOBD B20 and FHOBD B20 PG3 for 60%, 80% and 100% loads respectively.

From the figures it is clear that for all the fuel combinations NO_x emission increases with advancing ITs. Advancing fuel IT, peak pressure (PP) and heat release rate (HRR) increases due to longer ignition delay (ID). This results into higher peak in-cylinder gas temperatures which elevates the engine out NO_x emissions. Lower NO_x emissions from the CRDI engine are obtained for retarded fuel ITs as shown in Figs.17 and 18.

However, NO_x emissions are lower for BDFs as compared to mineral diesel operation. Lower gas temperature inside the CC and lower cetane number (CN) for BDFs operation could be the reasons for the observed trends.

At the same injection timing, FHOBD B20 with pyrogallol antioxidant additive, results into higher NO_x emissions due to higher in-cylinder temperature and peak pressure when injected at fixed IP of 600 bar. FHOBD B20 PG3 shows higher NO_x emissions compared to FHOBD and FHOBD B20 due to its comparatively higher BTE, PP and HRR associated with improved air-fuel mixture occurring in the engine cylinder.

4.3 Combustion characteristics

Combustion parameters such as ignition delay (ID), combustion duration (CD) and peak pressure (PP) for CRDI engine powered with diesel, FHOBD B100, FHOBD B20 and FHOBD B20 PG3 for varied fuel ITs when injected at a constant IP of 600 bar are shown Figs.19 to 24.

From the figures 19 to 22 it can be seen that at all fuel ITs the ID and CD of the BDFs are found to be higher than the diesel. Advancing the fuel, ITs for BDFs lowers both ID and CD while for diesel it is retarded timing. For the same engine operating conditions, the fuel properties result into these combustion patterns.

For a fixed fuel IP of 600 bar, the CD and ID of the engine fuelled with FHOBD and their blends show decreasing trend at 17°BTDC, respectively. This could be attributed to higher BTE, higher peak pressures observed at these ITs. Major

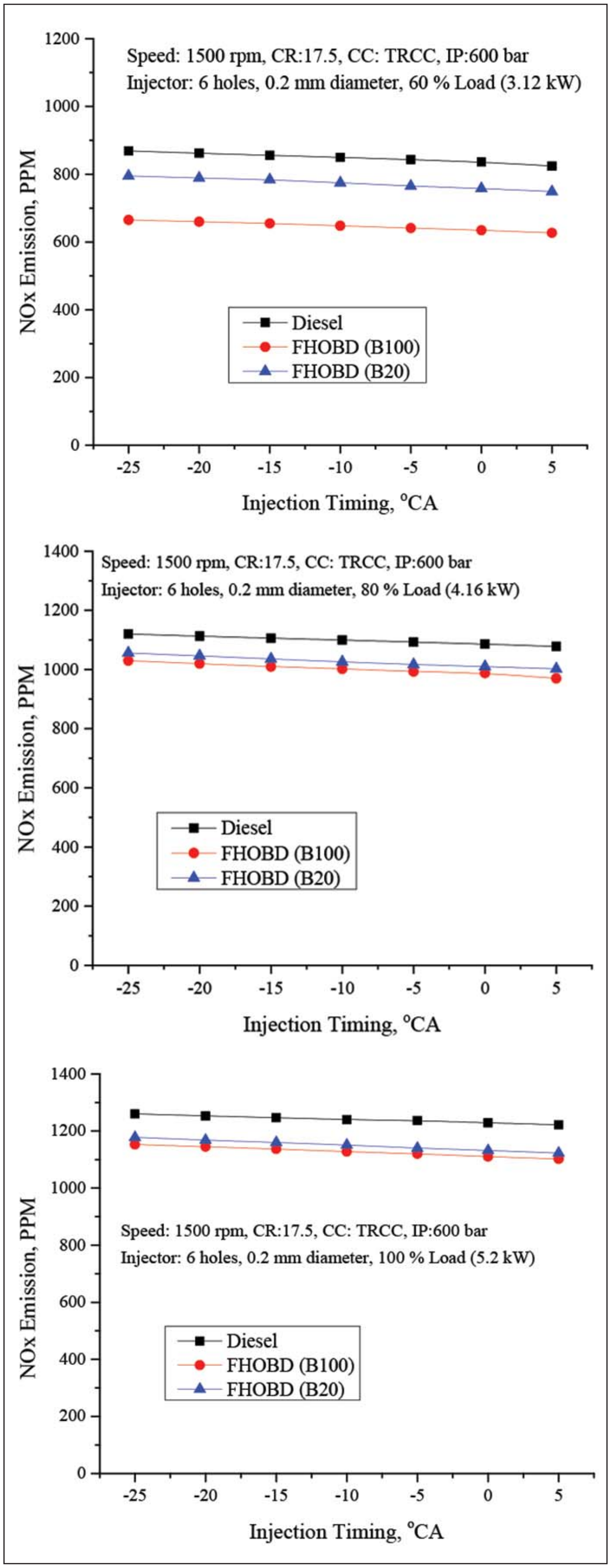

Fig.17: NO_x emissions variation with IT at 60%, 80% and 100% loads for FHOBD and FHOBD B20

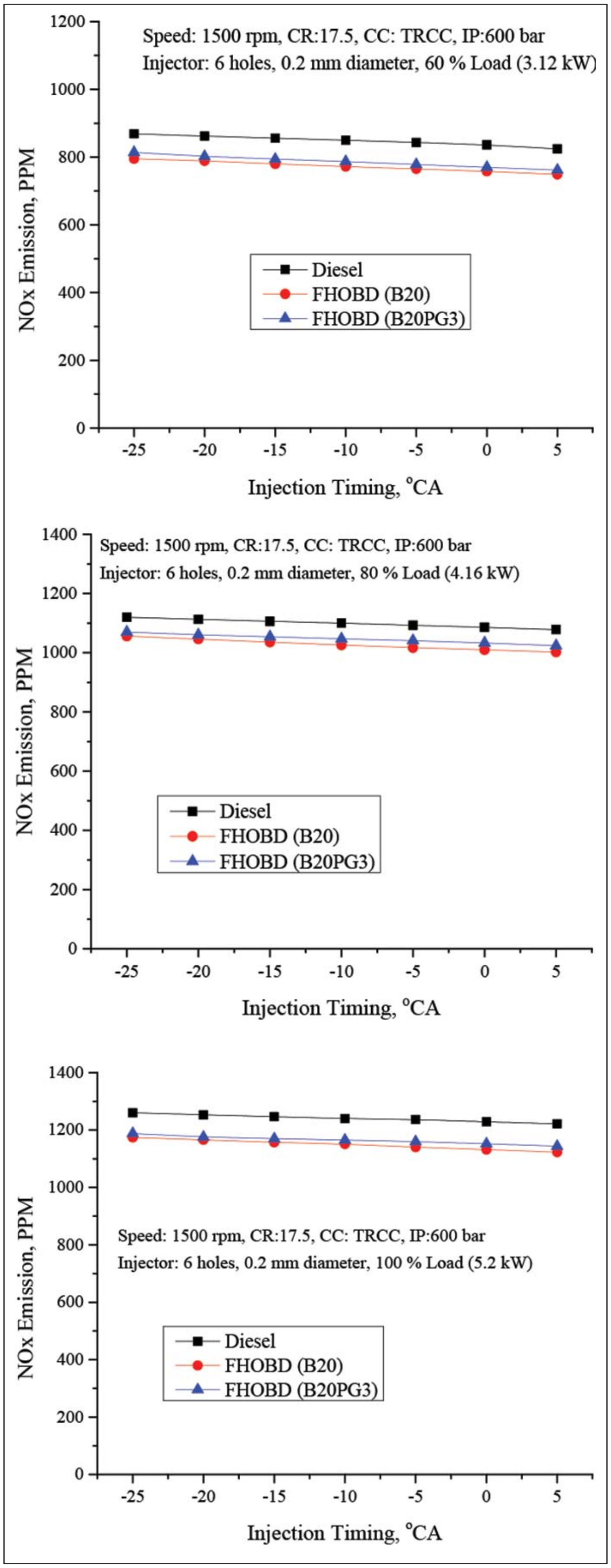

Fig.18: NO_x emissions variation with IT at 60%, 80% and 100% loads for FHOBD B20 and FHOBD B20PG3

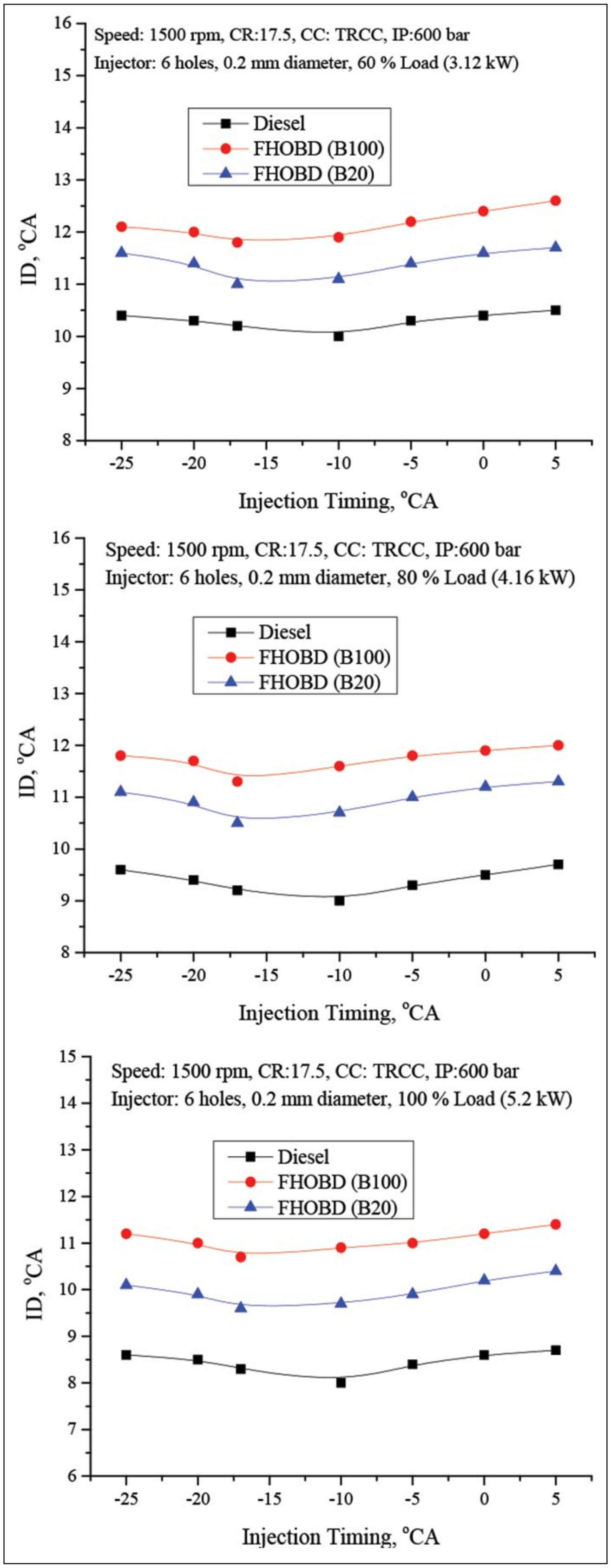

Fig.19: ID variation with IT at 60%, 80% and 100% loads for FHOBD, and FHOBD B20

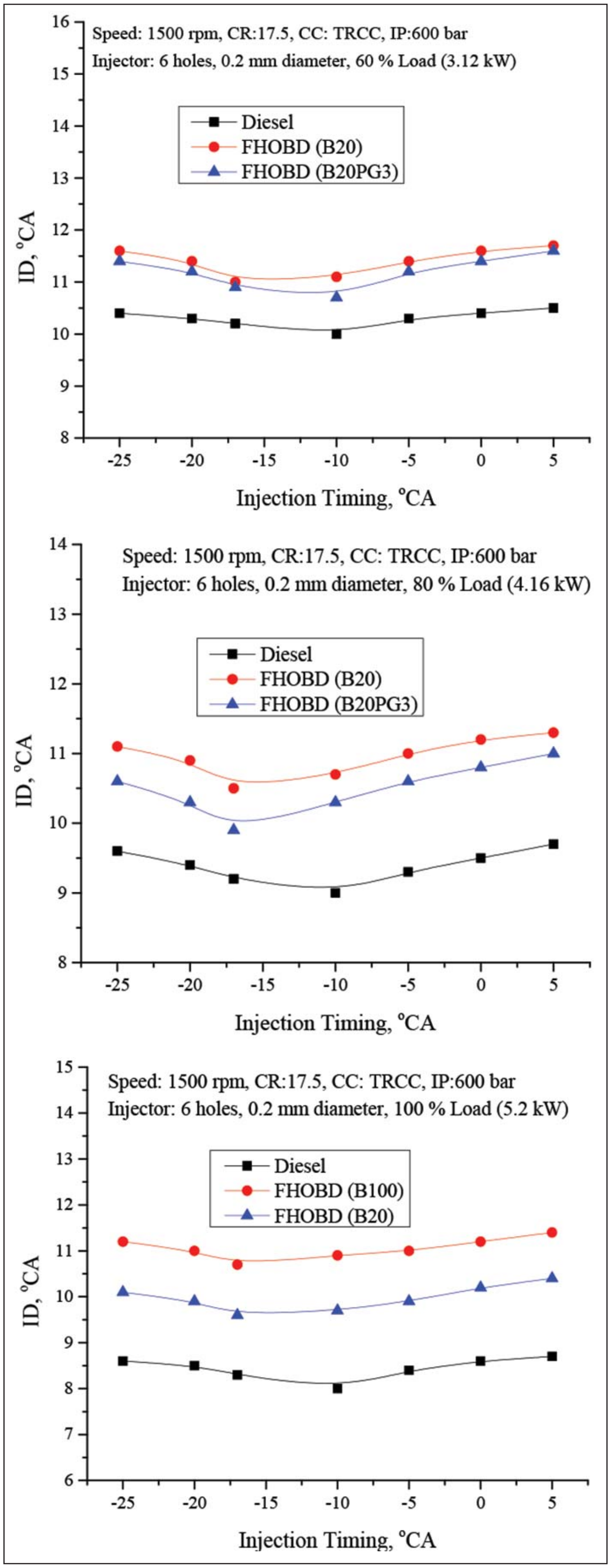

Fig.20: ID variation with IT at 60%, 80% and 100% loads for FHOBD B20 and FHOBD B20PG3

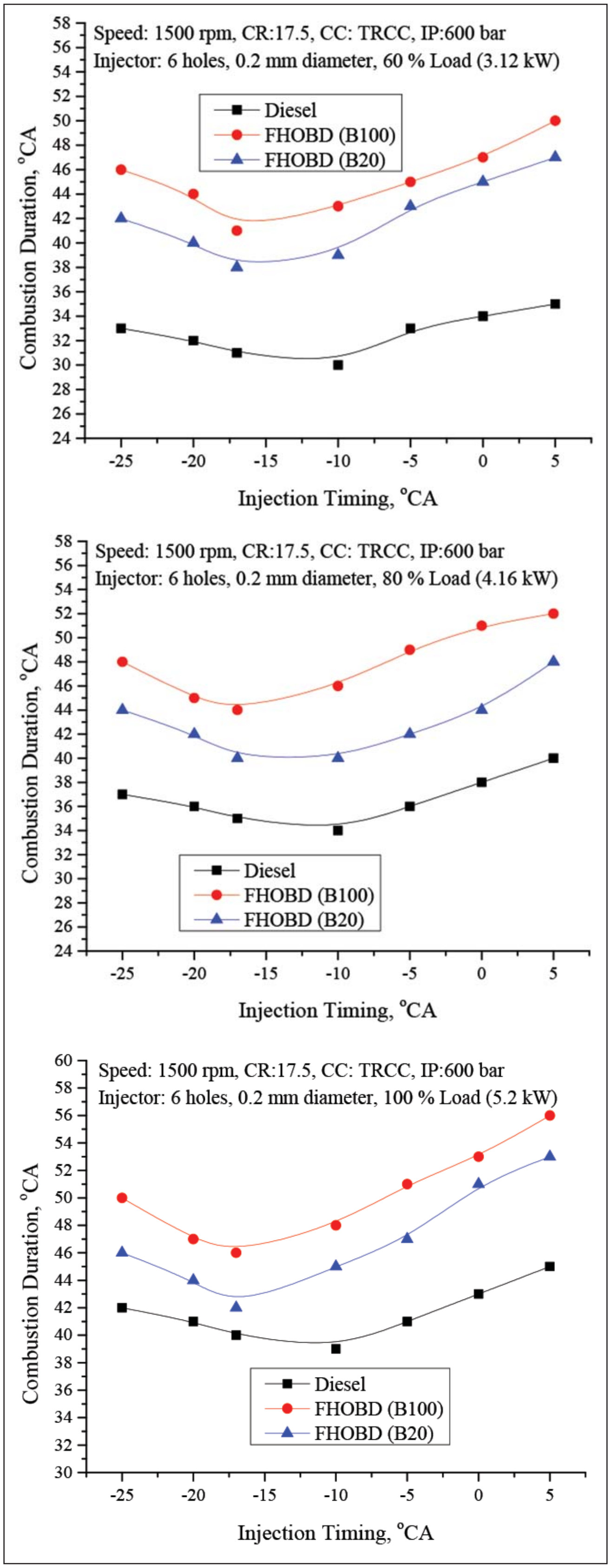

Fig.21: CD variation with IT at 60%, 80% and 100% loads for FHOBD and FHOBD B20

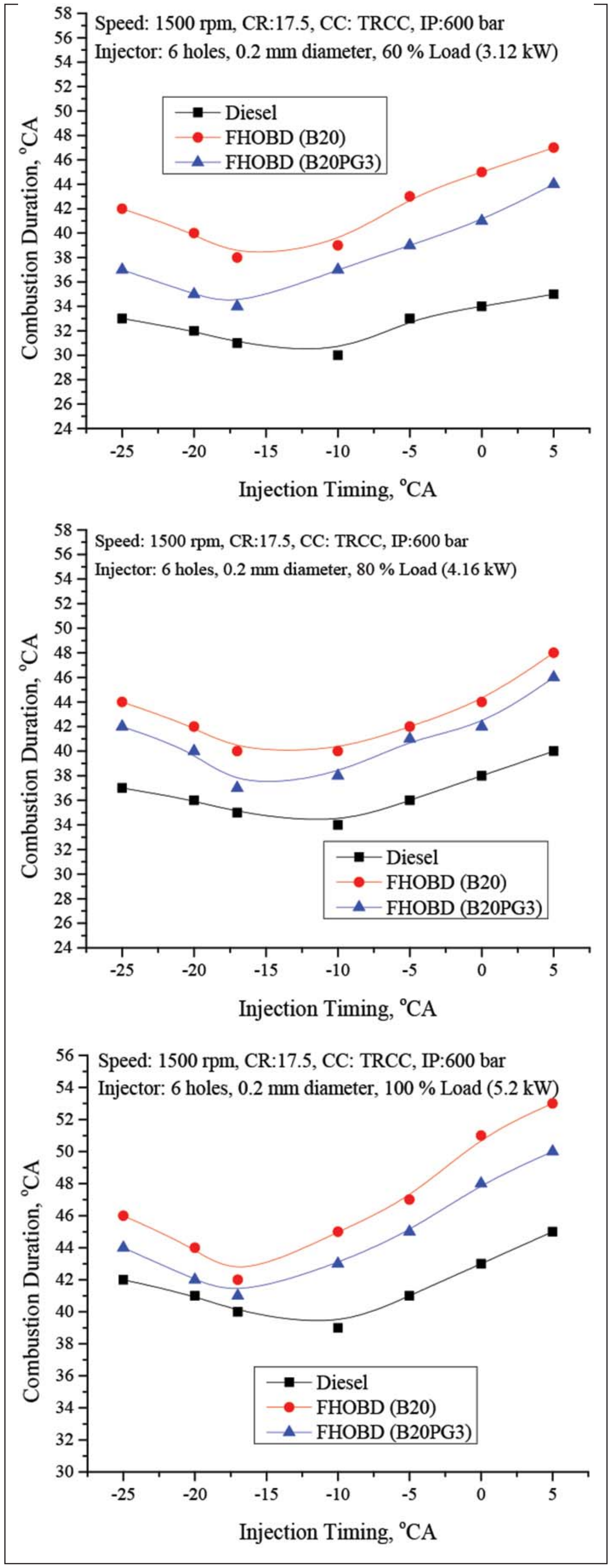

Fig.22: CD variation with IT at 60%, 80% and 100% loads for FHOBD B20 and FHOBD B20PG3

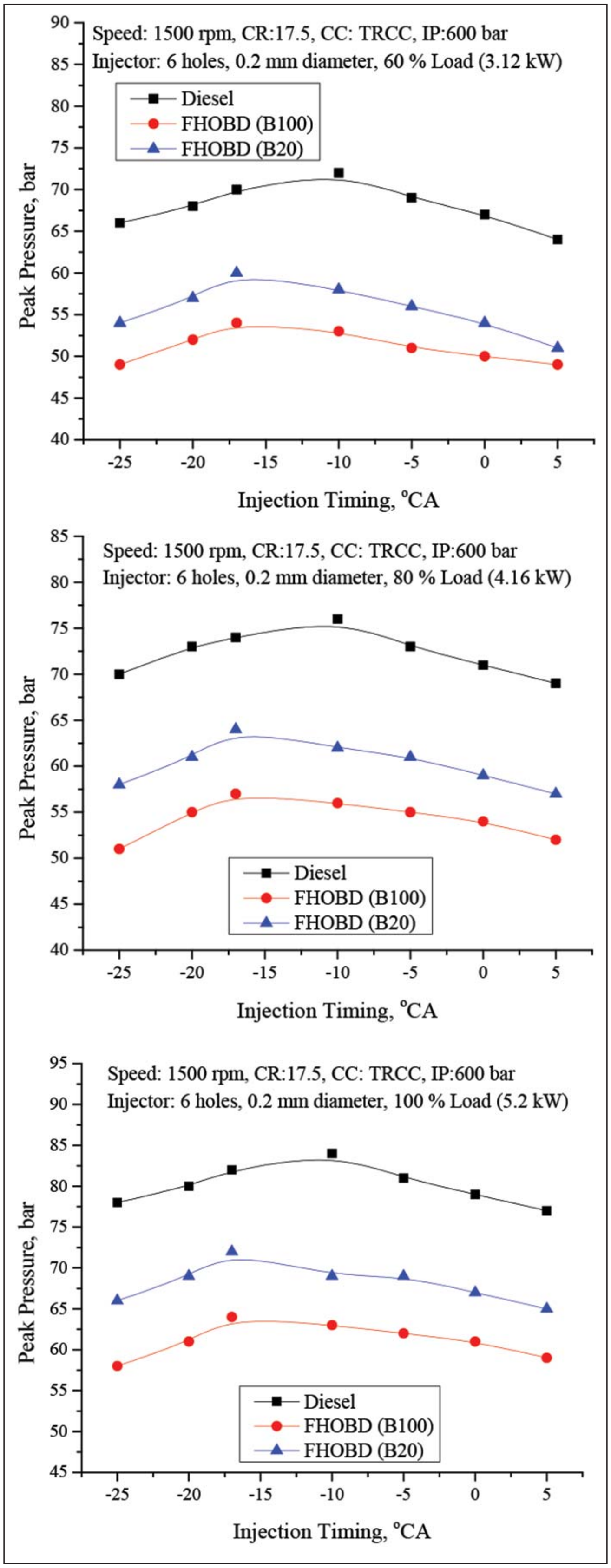

Fig.23: PP variation with IT at 60%, 80% and 100% loads for FHOBD and FHOBD B20

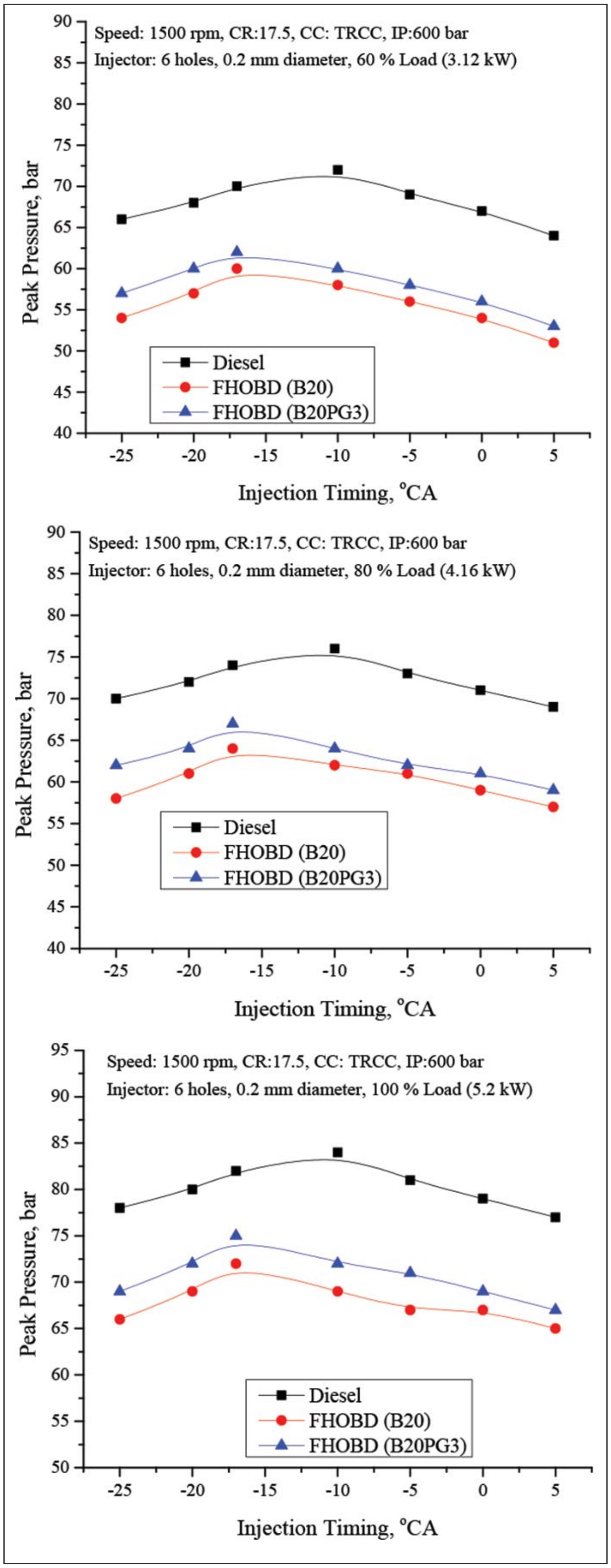

Fig.24: PP variation with IT at 60%, 80% and 100% loads for FHOBD B20 and FHOBD B20PG3

portion of the fuels burning in the premixed combustion phase at these optimized ITs results into lower values of CD and ID respectively. At the same injection timing, FHOBD B20 PG3, results into lower ID and CD compared to FHOBD and FHOBD B20. This could be due to its comparatively higher BTE, PP and HRR associated with uniform air-fuel mixture occurring in the engine cylinder. Pyrogallol biodiesel enhanced the oxidation stability of biodiesel and hence ID and CD are improved with the addition of antioxidant in the fuel.

Fig.23 depicts the effect of fuel IT on the peak pressure of CRDI engine fuelled with conventional diesel and FHOBD, and its blend with diesel (FHOBD B20) for 60%, 80% and 100% loads respectively.

Fig.24 depicts the effect of fuel IT on the peak pressure of CRDI engine fuelled with conventional diesel, diesel, FHOBD B100, FHOBD B20 and FHOBD B20 PG3 for 60%, 80% and 100% loads respectively.

From the Figs.23 and 24 it can be seen that at all fuel ITs the peak pressures of the BDFs are found to be lower compared to diesel. Higher viscosity and lower volatility of BDFs result into poor air-fuel mixture formation and hence lower PPs are obtained associated with comparatively lower BTE. In addition, the lower energy content of the BDFs resulted into lower magnitudes of PP and heat release rates (HRR). Advancing the IT favour BDFs with higher PP while it is retarding for diesel fuel. At an injection timing of 17^{o}BTDC, FHOBD B20PG3 results into higher PP, due to improved fuel properties and higher BTE at fixed IP of 600 bar. FHOBD B20PG3 shows higher PP compared to FHOBD, FHOBD B20 due to its higher calorific value and lower viscosity as well. Further major portion of FHOBD B20PG3 burns in the premixed combustion phase followed by FHOBD B20 and FHOBD respectively. Pyrogallol biodiesel enhanced the oxidation stability of biodiesel and hence PP is improved with the addition of antioxidant in the fuel.

5.0 Conclusions

Experimental investigations on the performance of CRDI diesel engine fuelled with B20 blends of fish oil and pyrogallol additive the following conclusions are drawn.

For CRDI engine operation at advanced injection timing of 17^{o}BTDC shows increases BTE, reduces emissions of smoke, HC, CO respectively with increase in NO_x emissions compared to diesel operation. Adding pyrogallol antioxidant in B20 blends of fish oil biodiesel improves engine performance with reduced emissions of smoke, HC, CO respectively.

CRDI engine operation with FHOBD B20PG3 the optimized conditions of 17^{o}bTDC, IOP of 600 bar 6-hole injector and TrCC combustion chamber resulted in increased BTE by 3.8%, 8.54% and NOx by 7.35%, 4.9%, decreased smoke by 15.22%, 43.07%, HC by 21.36%, 49.23%, CO by 12.5%, 34.8% when compared to B20 blends of Fish oil.

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