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Effects of Using Exhaust Gas Recirculation on the Performance, Combustion & Emissions of Diesel Engine with Manifold Injected Ethanol & Diesel-Ethanol Blend

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Abstract
The experimental investigations using ethanol in blended form with diesel as well as manifold injection form with diesel fuel with exhaust gas recirculation (EGR) were carried out on diesel engine. In the first part of the experimentation, 20% (by volume) ethanol - diesel blend with EGR varied from 5% to 20% was used. The manifold injection of ethanol to intake air at an injection angle of 5˚ATDC with injection duration of 27˚ CA (3 ms) was used in the second part of the experimentation keeping same EGR rates. From the test results, it has been observed that manifold injection of ethanol at 5˚ATDC with injection duration of 27˚ CA (3 ms) with 10% EGR was found to be optimal for the diesel engine operation in terms of performance, combustion and emission.

Key Word and Phrases
Oxygenates, Fumigation, Specific Heat, Exhaust Gas Recirculation, Optimisation.

1. Introduction

Diesel engines known for better injected fuel economy with higher thermal efficiency and power output. The engine exhaust NOx considered to be harmful and damaging to living things on earth. The EGR employment for diesel engine being the most effective method widely used to mitigate the oxides of nitrogen (NOx). Research work to mitigate the in-cylinder formation of NOx and PM has been taken up. Oxygenated fuels either in pure form or in blended form with diesel that supply extra oxygen for complete combustion thereby reducing PM and NOx emissions.

The experimental investigation to study the effect of EGR on the emission characteristics of a diesel engine showed reductions in NOx and exhaust gas temperature but increased emissions of particulate matter (PM), HC, and CO [1], [2]. An experimental test results have shown that NO_x found to be reduced by 98% and 5% increase in brake thermal efficiency (BTE) with optimized input parameters with EGR [3]. DEE proportion in the diesel blend was varied in an experimental study and revealed that 20 vol % DEE-diesel blend resulted in the optimum performance and emission characteristics. Furthermore, at 5 % EGR a simultaneous reduction in NO_x and smoke emissions was achieved amounted to 54% and 20% respectively. Also reduced NO_x emission at the expense of smoke in exhaust with increased EGR rate was noticed with pure diesel operation [4]. A review to study the potentiality of EGR to reduce NOx emissions concluded that with the usage of EGR controlled it [5]-[7]. An experimental work with a large butanol fraction, high EGR rate, and advanced fuel injection yielded better performance [8], [9] and with EGR, higher carbon deposits on engine parts was seen [10]. EGR of 15% could be adequate to yield reduction in NO, minimum possible smoke, CO, HC and reasonable BTE [11]. The experimental results with Jajoba biodiesel (JME) showed that EGR within a limited rate of 5–15% reduced NOx emissions with slightly lower BTE [12]. The experimental investigation on two cylinder, direct injection, air-cooled, diesel engine to study the influence of different quantities of EGR on exhaust temperature was carried out. It has been observed from the tests that NOx level decreases, while smoke and PM level increases with 25% EGR besides no significant changes in the BTE [13]. Ethanol blended diesel fuel from 0% to 15% at IT of 21^o, 24^o, 27^o, 30^{o}and 33^o CA BTDC showed that with increased percentage of ethanol, BSFC and NOx increased with with lower BTE and HC [14].

The influence of methanol/diesel and ethanol/diesel fuel blends on the combustion characteristic of an IDI diesel engine at IT of 25^o, 20^o (original IT) and 15^o CA before top dead centre (BTDC) by using five different fuel blends yielded higher peak pressure, heat release rate (HRR), ignition delay (ID) and combustion duration (CD) with advanced fuel delivery timing. Increase in ID and to decrease in CD was also noticed with increasing methanol or ethanol amount in the fuel blends [15].

The effect of fumigation of diethyl ether on the performance of diesel engine indicated that the BTE is enhanced by 10.47 and 2.46% with the fumigation of DEE at the rate of 120 g/h and 240 g/h respectively. The lower NO emission was noticed with both flow rates, whereas, both CO and HC emissions were higher at the flow rate of 240 g/h and diesel [16]. Bioethanol fumigation yielded longer ID of 2–3^o CA and flow rate of 0.48 kg/h could be better in terms of higher BTE and lower emissions [17]. BTE, NOx and CO emissions were found to be dropped at lower loads and increased with higher loads for 1.39 Kg/hr ethanol flow compared to diesel fuel [18]. The optimum percentage for ethanol fumigation could be 20% [19]. The tests to evaluate the influence of ethanol injection into inhaling air at the inlet manifold on the performance of a diesel engine were carried out. Drop in engine efficiency and increased CO and THC emissions was observed with addition of ethanol, the mixing of 0.4% di-tert-butyl peroxide additive in the main fuel results in slightly enhanced efficiency and reduced CO and THC emissions. It is concluded that the injection of ethanol which significantly reduced the cylinder temperature is the best method of mitigating the NOx in the engine exhaust [20].

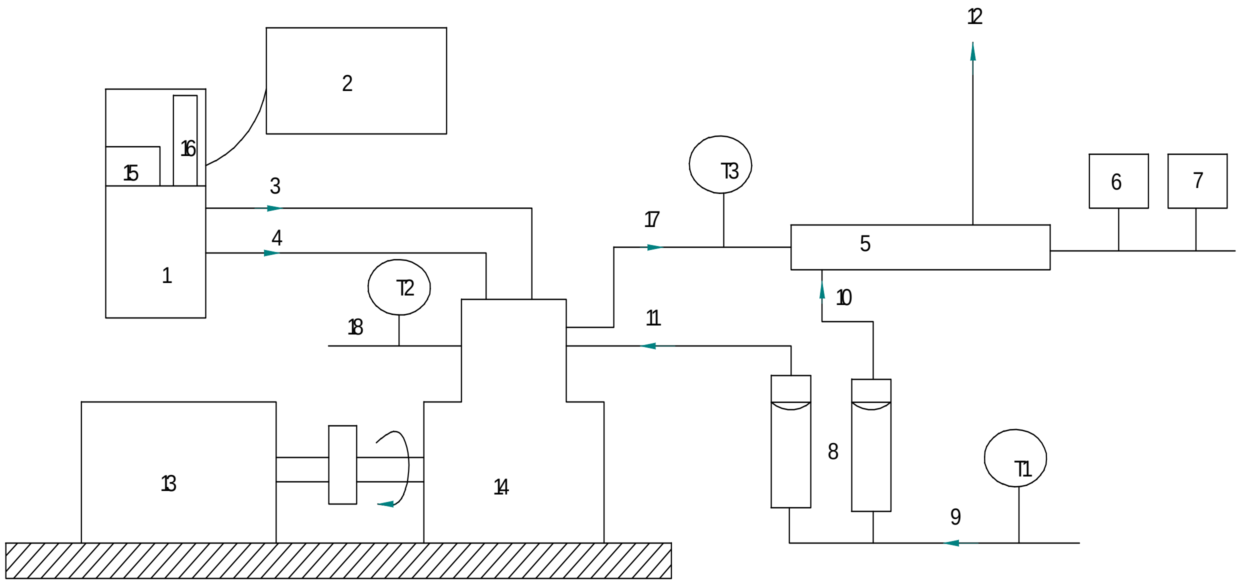
From the review of the literatures over the usage of ethanol in diesel engine, although, massive works have been done on the diesel- ethanol blends, it has been noticed that very limited works have been carried out on diesel engine with alcohol fumigation. In this context, experimental investigations were carried out on a single cylinder four stroke direct injection diesel engine operated on diesel by injecting the alcohol to the intake air in the manifold with an optimum IT of 5^o ATDC and durations of 27^{o}CA (3 ms) using ECU and suitable injector and diesel-ethanol 20 blends with different percentage of EGR to study its effect on the performance, combustion and emission characteristics of diesel fuelled engines.

2. Experimental Set up & Methodology

Experimental tests were carried out on a Kirloskar TV1 type, four stroke, single cylinder, diesel engine test rig shown in Fig. 1 where eddy current dynamometer loaded the engine. The volumetric fuel flow rate of diesel fuel was measured using a burette and stopwatch method. The engine speed was maintained constant at 1500 rev/min. Test were carried out at an injection pressure of 205 bar with an injector of 3 holes of 0.3 mm at an IT of 23^o BTDC. Figures 2 and 3 shows the circuit arrangement and electronic control unit (ECU) (i.e. Digital PID controller) for ethanol flow. The ethanol was injected into the inlet manifold at an injection angle of 5^o ATDC with injection duration of 27^{o}CA (3 ms) with the help of electronic control unit (ECU) and injector system. Ethanol was stored in closed container provided with fuel pump to supply the ethanol to the fuel injector at a low pressure of 0.2 MPa. The ethanol injector was fitted to the intake manifold for fumigation. One pole of the pump is connected to the negative pole of the battery and other pole to the ECU. The ECU controls the operation of ethanol fuel injector. A 12 Volt battery is used for the power supply, whose positive terminal is connected to positive pole of the injector, while the other end of the injector is connected to the ECU, which controls injector opening timing and duration. The control knob provided in the ECU is used to vary the injection duration within the specified range. Based on the pre-set timing, the injector will be opened for injection for particular duration and then closed after injection. An optical sensor which was fixed to the engine housing sends the input signal to the ECU for the injector opening when a reflective tape attached to the flywheel was exactly in front of sensor when the piston was at some pre-set angle with respect to top dead center (TDC). Meanwhile, the ECU actuate the pump to operate. Since the quantity of ethanol injected to the manifold is very less compared to diesel at all IT and durations, only loads of 60%, 80% and 100% are considered throughout the experimentation. In addition, diesel-20% ethanol blend was also used for experimentation, as it was found to be optimal from the point of view of performance and emissions. The emission characteristics were measured by HARTRIDGE smoke meter and five gas analyser. Finally, the results obtained were analysed. The specification of the compression ignition (CI) engine is given in Table 1. Properties of the fuels used viz. HS diesel and ethanol are shown in Table 2.

Table 1 Specifications of the Engine

Sl No	Parameter	Specifications
1	Type	TV1 (Kirlosker make)
2	Software used	Engine soft
3	Nozzle opening pressure	200 - 205 bar
4	Governor type	Mechanical centrifugal type
5	No. of cylinders	Single cylinder
6	No. of strokes	Four stroke
7	Fuel	H. S. Diesel
8	Rated power	5.2 kW (7 HP at 1500 RPM)
9	Cylinder diameter (Bore)	0.0875 m
10	Stroke length	0.11 m
11	Compression ratio	17.5: 1
Air measurement manometer		
12	Made	MX 201
13	Type	U- Type
14	Range	100 – 0 – 100 mm
Eddy current dynamometer		
15	Model	AG – 10
16	Type	Eddy current
17	Maximum	7.5 (kW at 1500 - 3000 RPM)
18	Flow	Water must flow through Dynamometer during the use
19	Dynamometer arm length	0.180 m
20	Fuel measuring unit – Range	0 - 50 ml



1- Control Panel, 2 – Computer system, 3 – Diesel flow line, 4 – Air flow line, 5 – Calorimeter, 6 – Exhaust gas analyser, 7– Smoke meter, 8 – Rotameter, 9, 11- Inlet water temperature, 10 – Calorimeter inlet water temperature, 12– Calorimeter outlet water temperature, 13 – Dynamometer, 14– CI Engine, 15– Speed measurement, 16– Burette for fuel measurement, 17– Exhaust gas outlet, 18– Outlet water temperature, T1-Inlet water temperature, T2 – Outlet water temperature, T3 – Exhaust gas temperature

Fig. 1 Experimental Setup

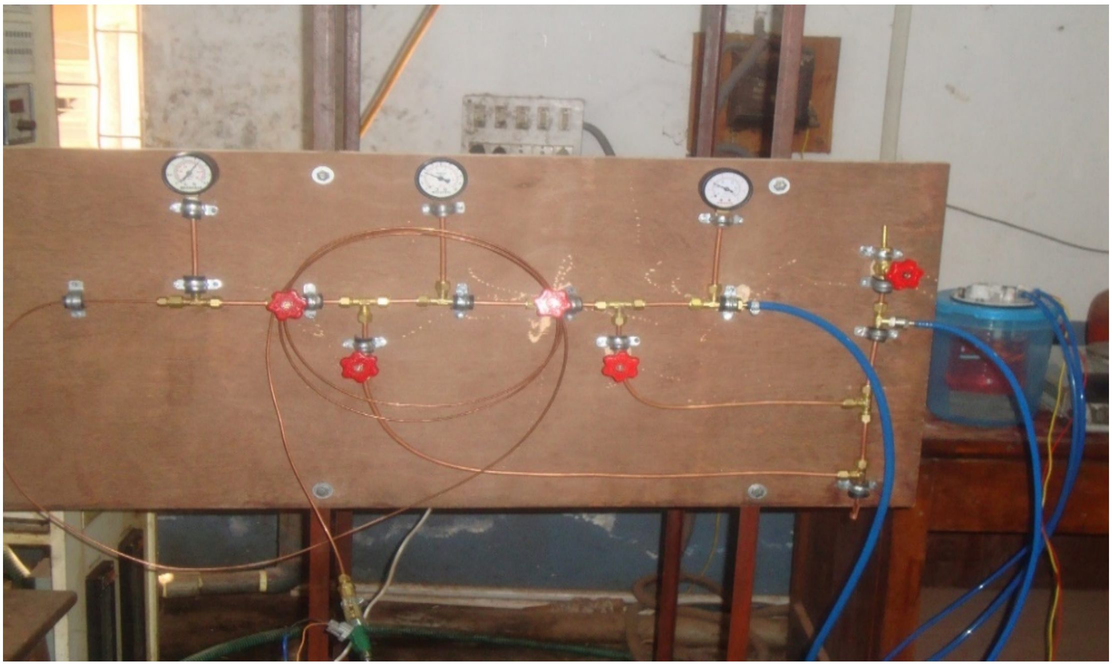


Fig. 2 Circuit for Ethanol Flow

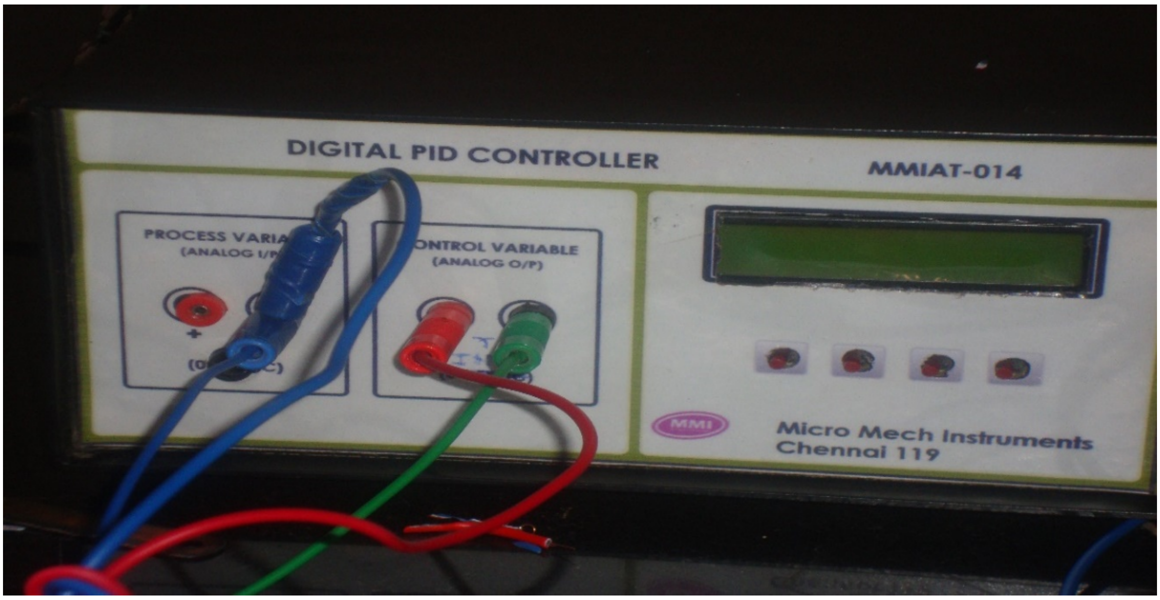


Fig. 3 Electronic Control Unit

Table 2 Properties of the fuels used

Sl No	Property	Diesel	Ethanol
1	Molecular Weight	181 g/mol	46 g/mol
2	Molecular Formula	$C_{13}H_{24}$	C_2H_6O
3	Appearance	Light yellow liquid	Colorless liquid
4	Density	850 kg/m^3	789 kg/m^3
5	Boiling point	266^o C	78^{o}C
6	Flash point	85° C	14 °C
7	Volatility	Volatile	Volatile
8	Kinematic viscosity at 40^o C	3.05 cSt	0.795cSt
9	Auto-ignition temperature	316 ^{o} C	422^o C
10	Heating value	43000 kJ/kg	29700 kJ/kg
11	Surface tension at 20^o C	0.023 N/m	0.022 N/m
12	Latent heat of vaporization	250 kJ/kg	922 kJ/kg
13	Flammability	Flammable	Flammable
14	Cetane number	45-55	8
15	Carbon content (% weight)	84-87	52.2
16	Hydrogen content (% weight)	33-16	13.1
17	Oxygen content (% weight)	0	34.7
18	Stoichiometric air-fuel ratio	15	9

3. Results and Discussions

This section explains the performance of the diesel engine operated on diesel with the injection of ethanol into the intake manifold at different injection angles and durations as well as with diesel-ethanol 20 blends.

3.1 Performance Characteristics

3.1.1 Brake Thermal Efficiency:

Figures 3.1 (a) and (b) visualizes the variation of BTE of an engine operated with manifold injected ethanol and diesel-ethanol 20 blends with different EGR rates. The BTE was found be decreased slightly with EGR rate at all engine loads. It may be due to the EGR into the cylinder dilute the charge by displacing fresh air entering the combustion chamber (CC) with carbon dioxide and water vapour and thus lowers oxygen concentration and flame temperature of the working fluid in the CC. In addition, the exhaust gas in the CC acts as an inert gas, diminishes the rate of auto ignition reactions because of increased ID and hence lower amount of oxygen in the intake mixture is available for combustion that lowers the effective air–fuel ratio.

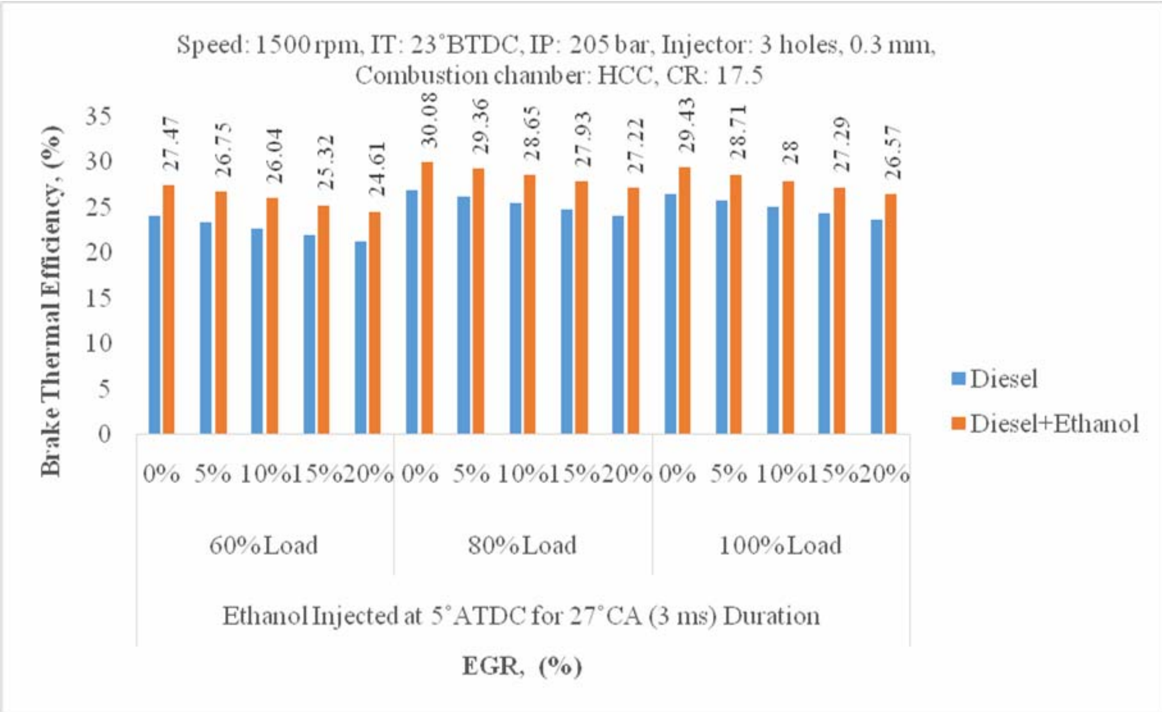


Fig. 3.1 (a) Variation of BTE with the EGR rates for manifold injected ethanol

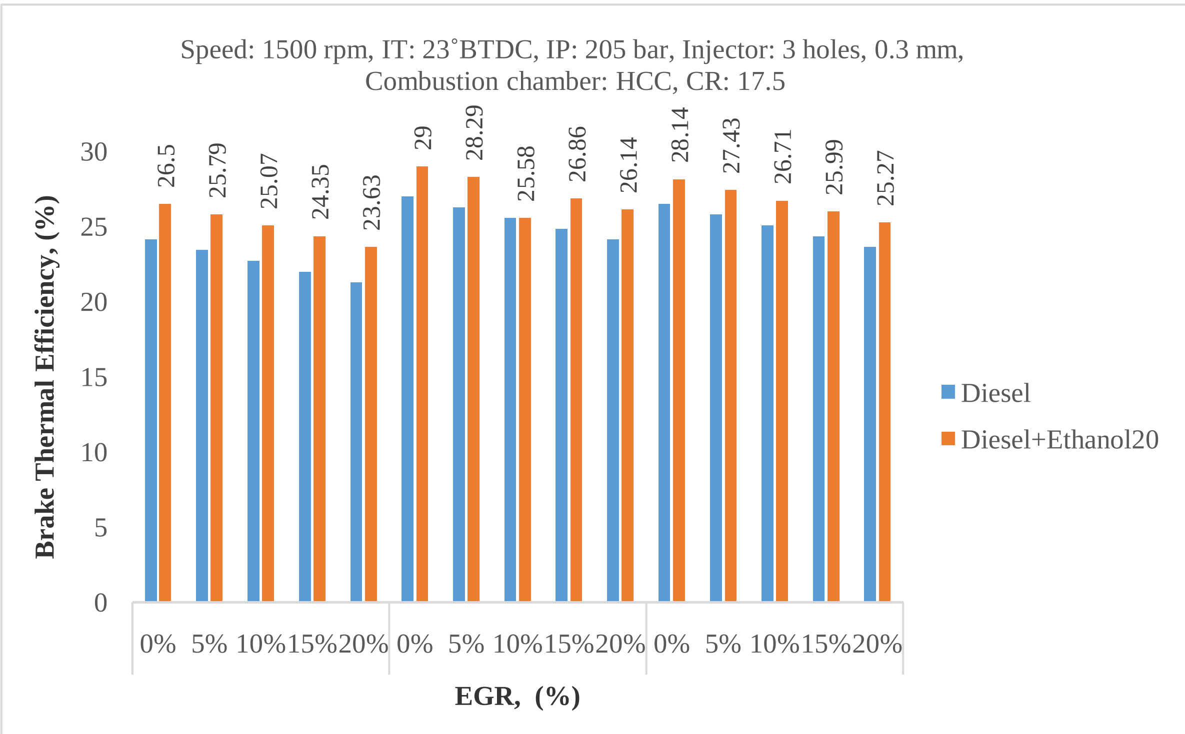


Fig. 3.1 (b) Variation of BTE with the EGR rates for diesel- ethanol blend

3.2 Emission Characteristics

3.2.1 Smoke Emissions:

Figures 3.2 (a) and (b) depicts the variation of smoke of an engine operated with manifold injected ethanol and diesel-ethanol 20 blends with different EGR rates. The smoke of the exhaust gas quantitates the particulate matter (PM) present in the exhaust gas. The smoke emissions were found to be lower for ethanol injection and blending compared to diesel at all loads. The possible reason for this may be due to good mixture formation and presence of oxygen in the ethanol. Smoke opacity of the exhaust was found to be increased when the engine is operated with EGR compared to Non- EGR operation at all loads. This is because, EGR with water vapour dilute the mixture and reduces availability of oxygen for combustion of fuel.

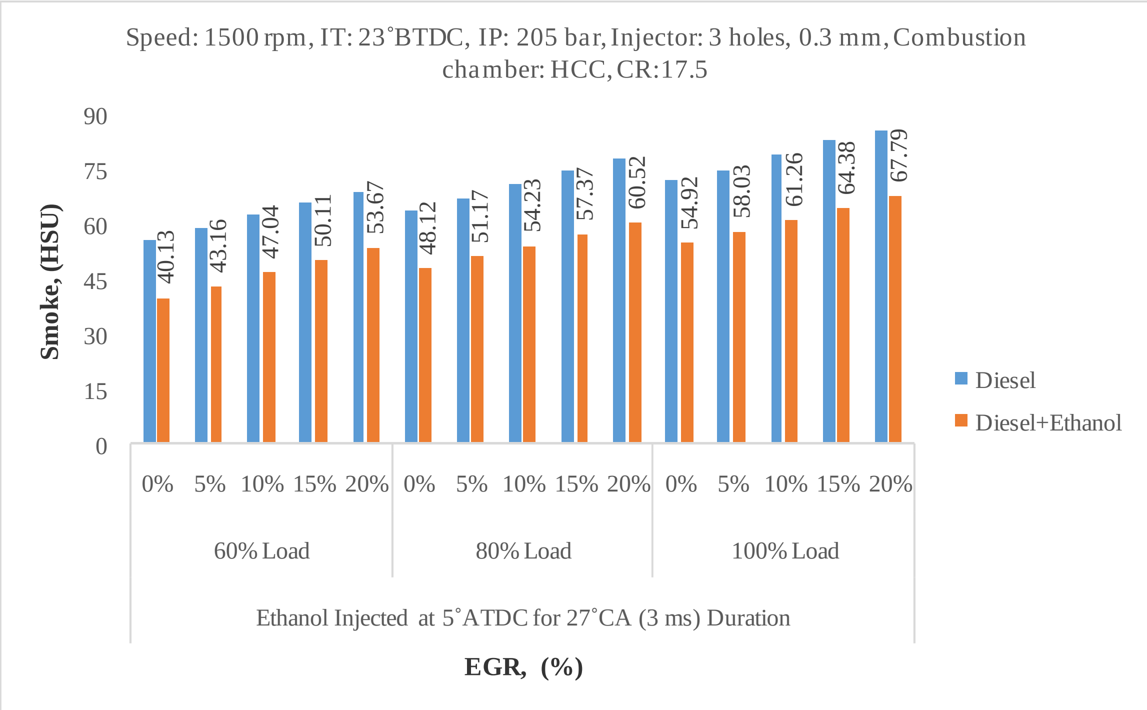


Fig. 3.2 (a) Variation of smoke opacity with EGR rates for manifold injected ethanol

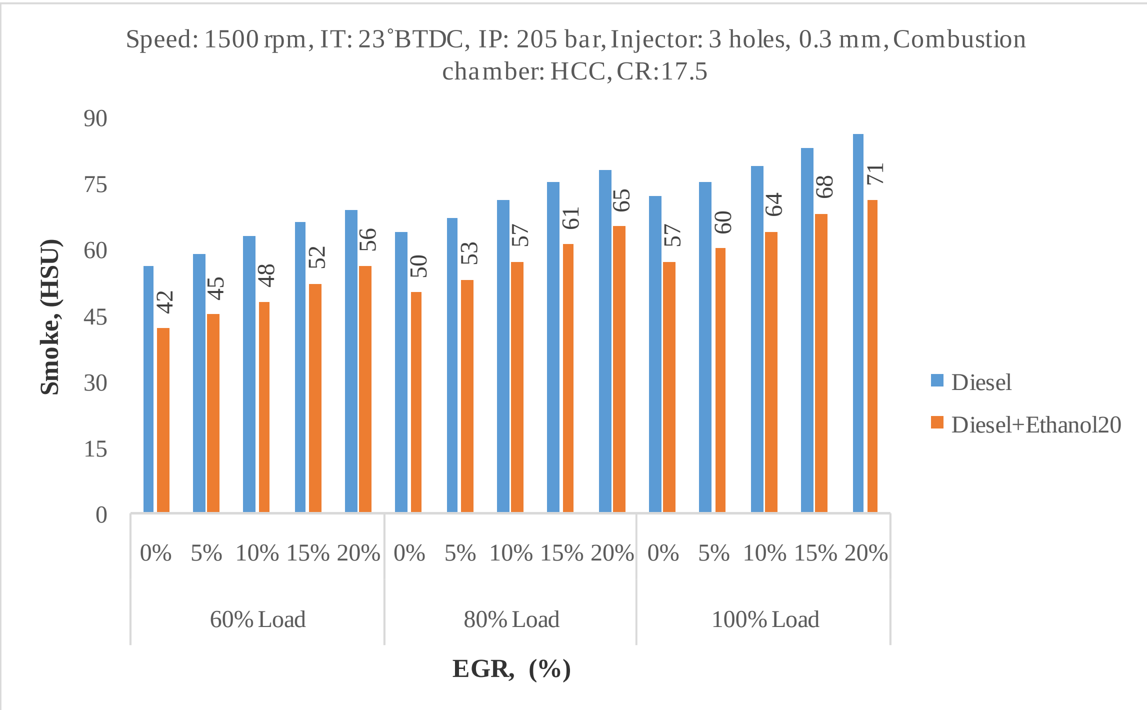


Fig. 3.2 (b) Variation of smoke opacity with EGR rates for diesel- ethanol blend

3.2.2 HC and CO Emissions:

Figures 3.3 (a) and (b) and Figures 3.4 (a) and (b) evidences the variation of unburned HC and CO emissions of an engine operated with manifold injected ethanol and diesel-ethanol 20 blends respectively with different EGR rates. It has been observed from the graphs that HC and CO emissions were increased with increase in the EGR rate at all engine loads. HC and CO emissions are generally decreases with increase in combustion temperature and homogeneity of the mixture. Because of EGR induction, the inlet mixture gets diluted and lowers excess oxygen available for the combustion that cause rich air–fuel mixtures to exists at different locations inside the CC that results in reduced combustion temperature. This heterogeneous mixture does not combust completely due to oxygen deficiency and results in higher HC and CO emissions.

3.2.3 NOx Emissions:

Figures 3.5 (a) and (b) presents the variation of Nitric oxide (NO) emissions of an engine operated with manifold injected ethanol and diesel-ethanol 20 blends respectively with different EGR rates. NO emissions were recorded to be reduced with increased EGR rates. This is because of dilution of the inlet charge due to EGR, which minimized oxygen concentration, increase the specific heat of the intake mixture that requires more energy to preheat the incoming mixture that tend to slows down the combustion speed and reduced the adiabatic flame temperature and, thereby, the combustion temperature and hence NO emissions are reduced. Therefore, NO concentration decreases as CI engine inlet charge is diluted at a constant fuelling rate.

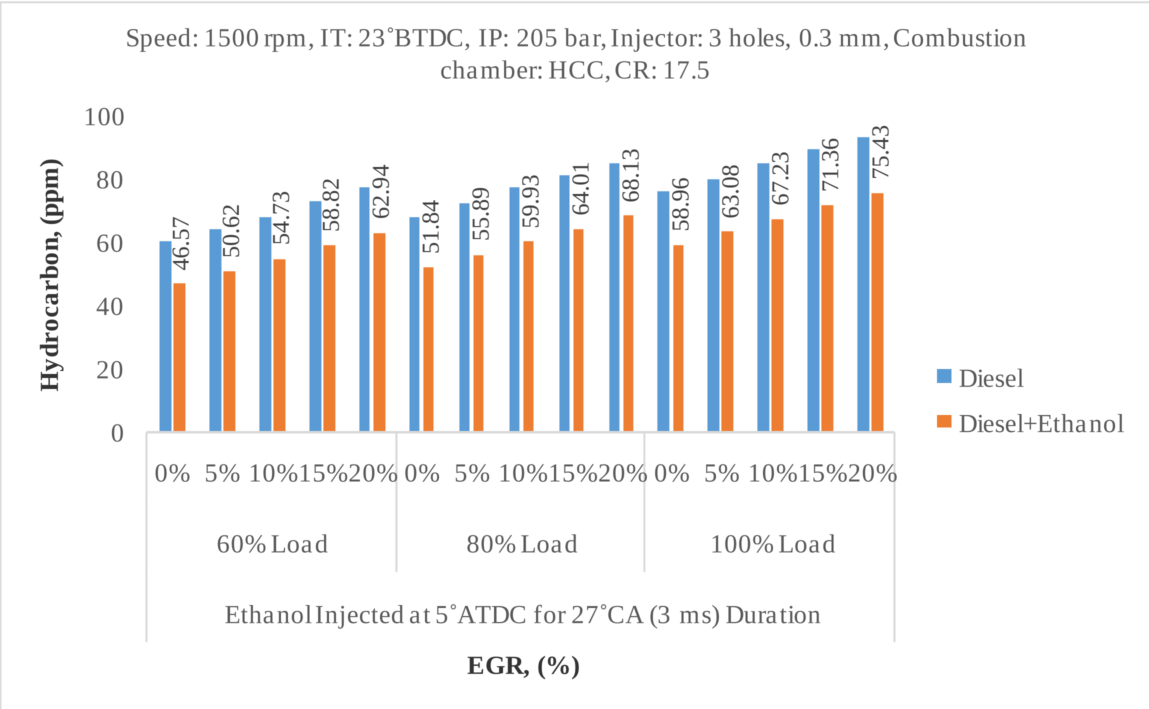


Fig. 3.3 (a) Variation of HC emissions with the EGR rates for manifold injected ethanol

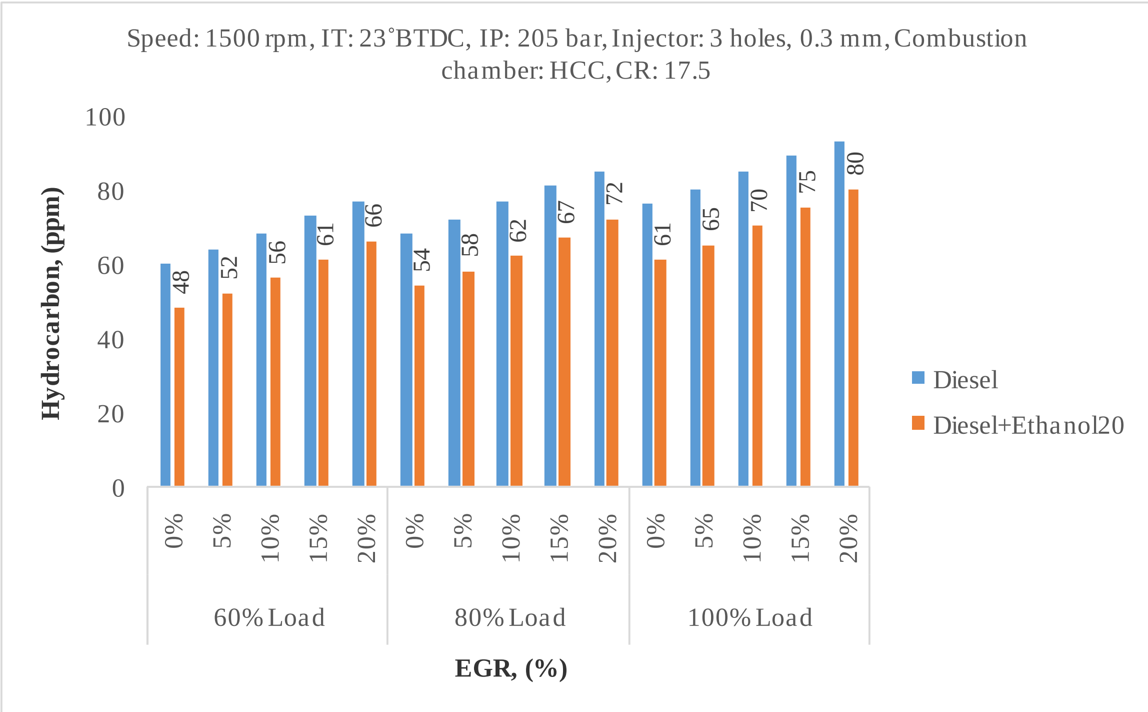


Fig. 3.3 (b) Variation of HC emissions with the EGR rates for diesel- ethanol blend

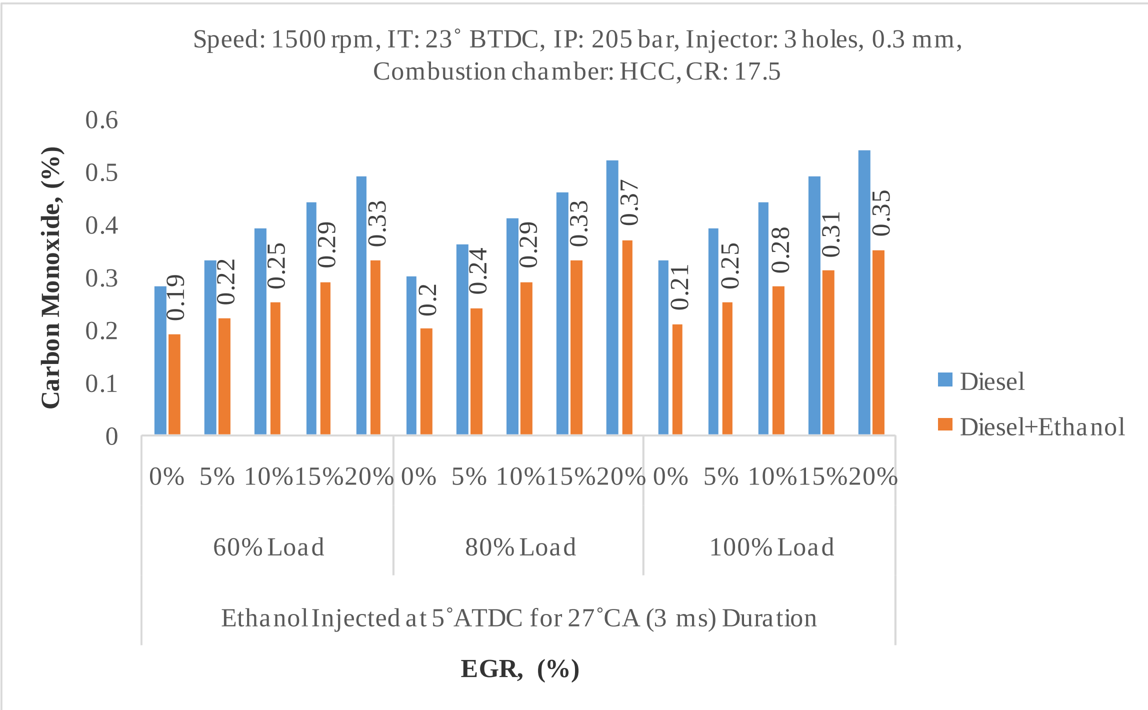


Fig. 3.4 (a) Variation of CO emissions with the EGR rates for manifold injected ethanol

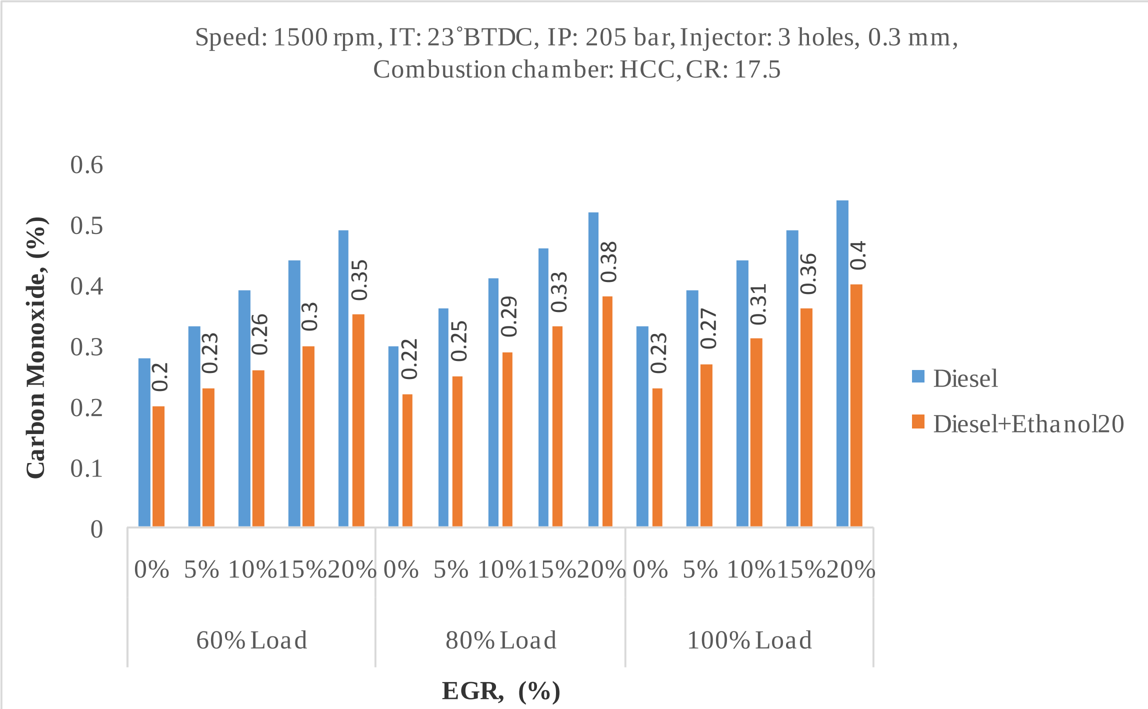


Fig. 3.4 (b) Variation of CO emissions with the EGR rates for diesel- ethanol blend

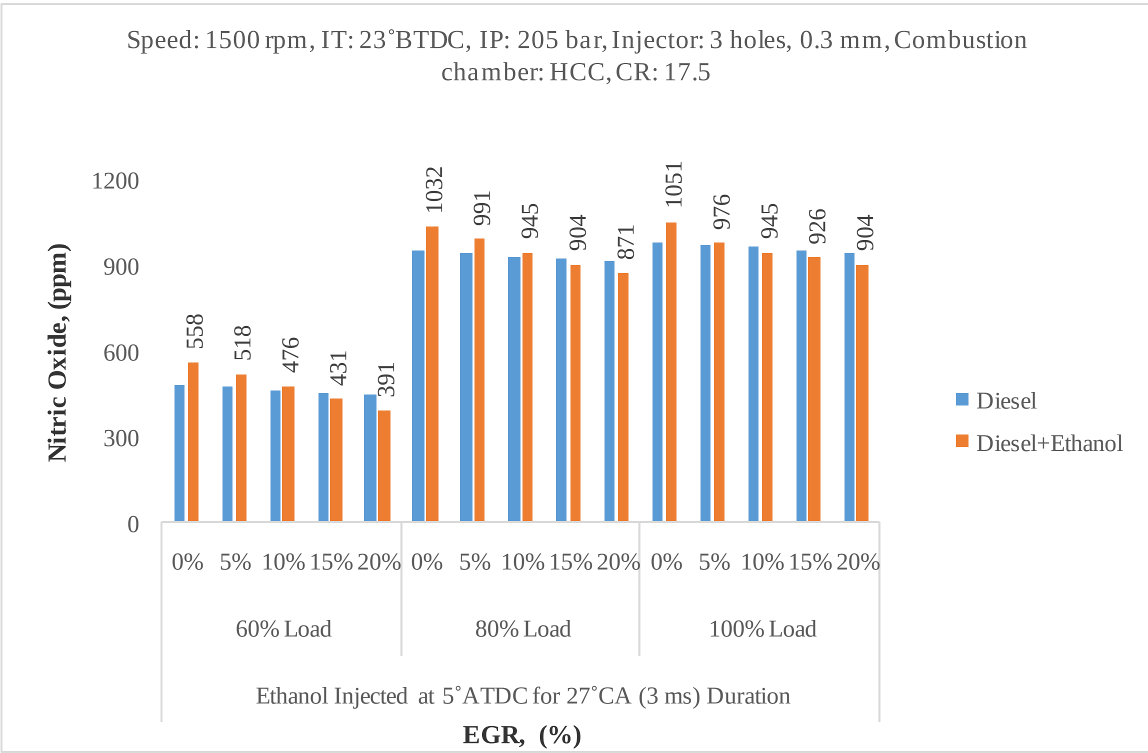


Fig. 3.5 (a) Variation of NO emissions with the EGR rates for manifold injected ethanol

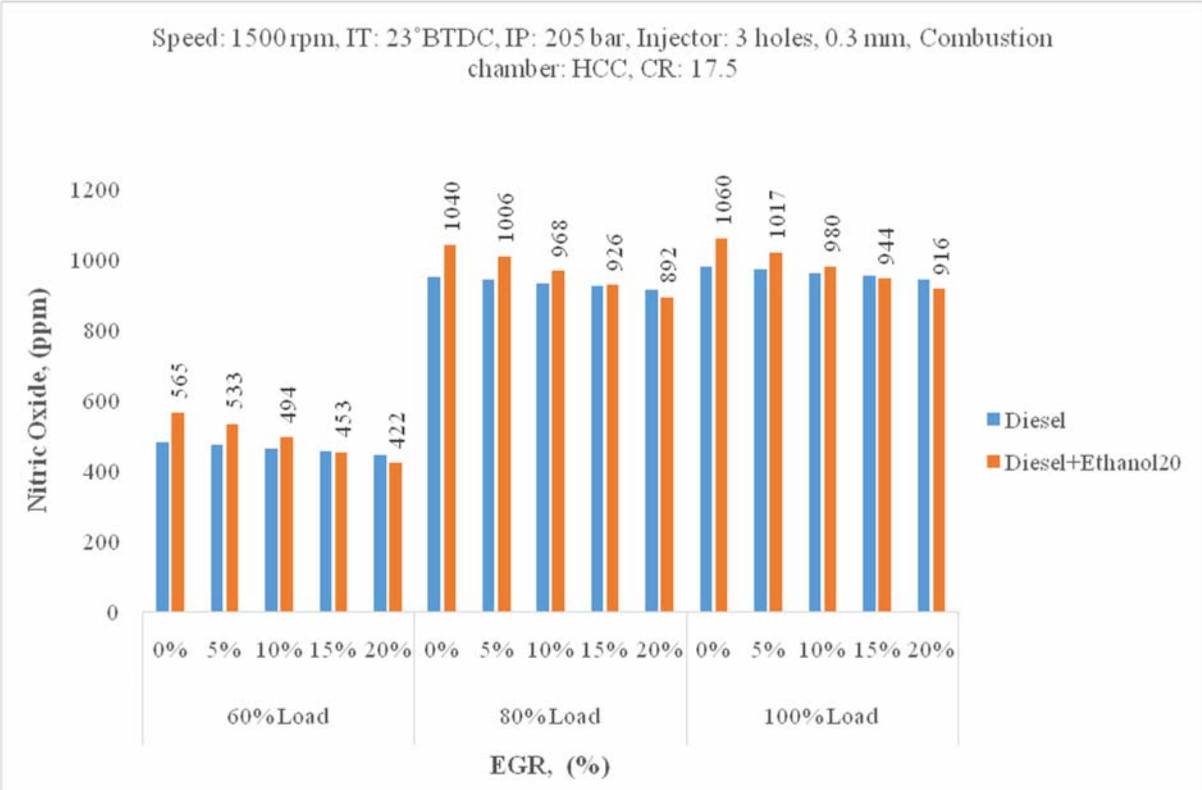


Fig. 3.5 (b) Variation of NO emissions with the EGR rates for diesel- ethanol blend

3.3 Combustion Characteristics

3.3.1 Peak Pressure:

Figures 3.6 (a) and (b) evidences the variation of peak pressure (PP) of an engine operated with manifold injected ethanol and diesel-ethanol 20 blends respectively with different EGR rates. It has been observed from the graph that PP reduced slightly with increased EGR rate at all loads. This is because of increased oxygen deficiency and specific heat of the intake mixture resulting from the higher EGR rate led to incomplete combustion and reduced combustion temperature that results in drop in PP marginally.

3.3.2 Combustion Duration:

Figures 3.7 (a) and (b) presents the variation of combustion duration (CD) of an engine operated with manifold injected ethanol and diesel-ethanol 20 blends respectively with different EGR rates. It has been noticed that from the graphs that CD increases with EGR rate at all loads. The reason for this may be due to dilution of the intake mixture with EGR, which makes the mixture to behave like an inert gas, which increases the specific heat of the mixture and does not involve in thermal reaction that led to drop in combustion temperature that could slows down the combustion speed, which elongated the CD.

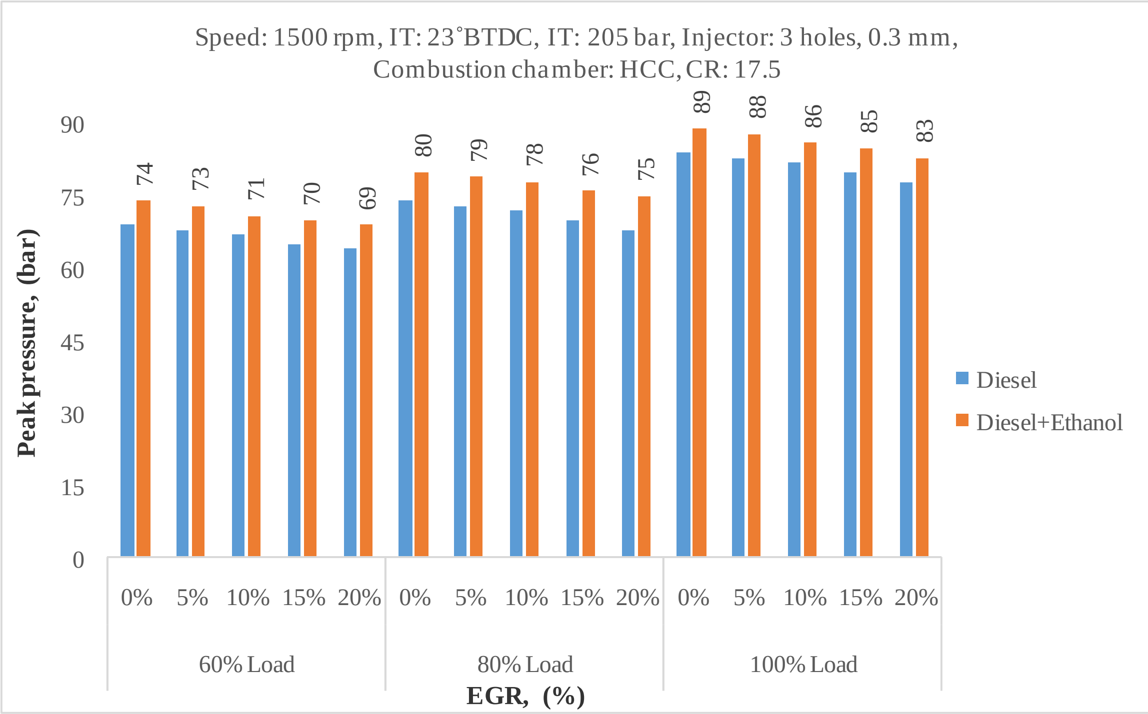


Fig. 3.6 (a) Variation of Peak pressure with the EGR rates for manifold injected ethanol

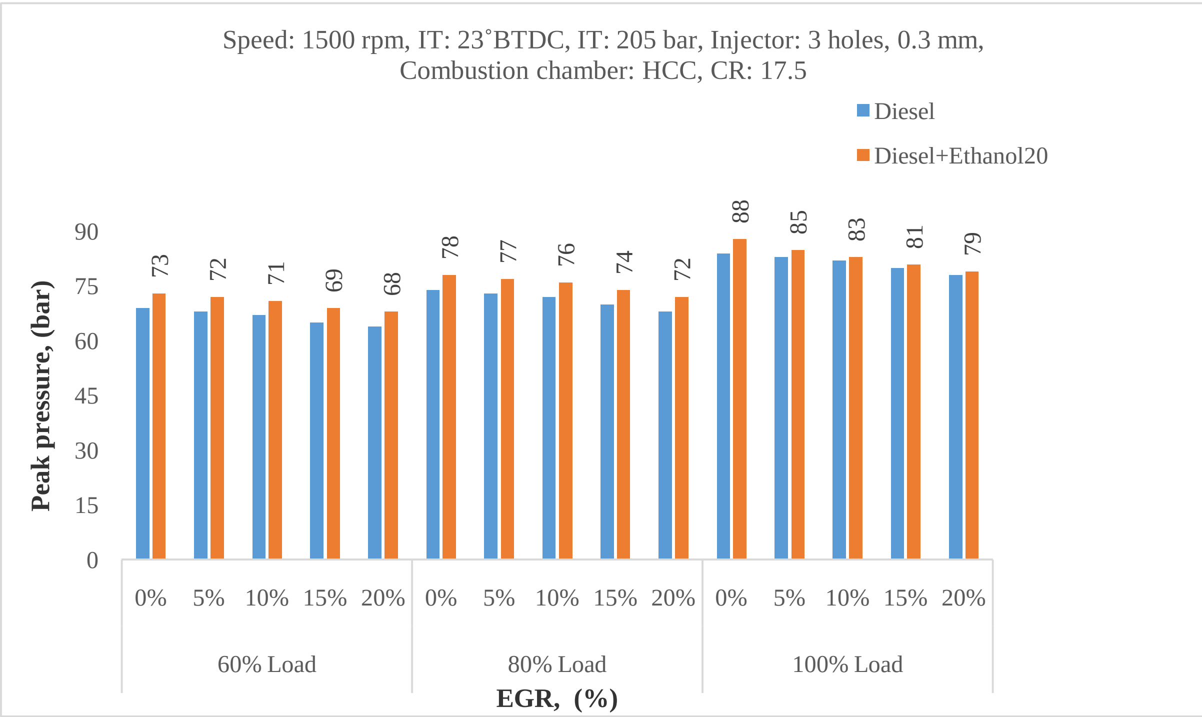


Fig. 3.6 (b) Variation of Peak pressure with the EGR rates for diesel- ethanol blend

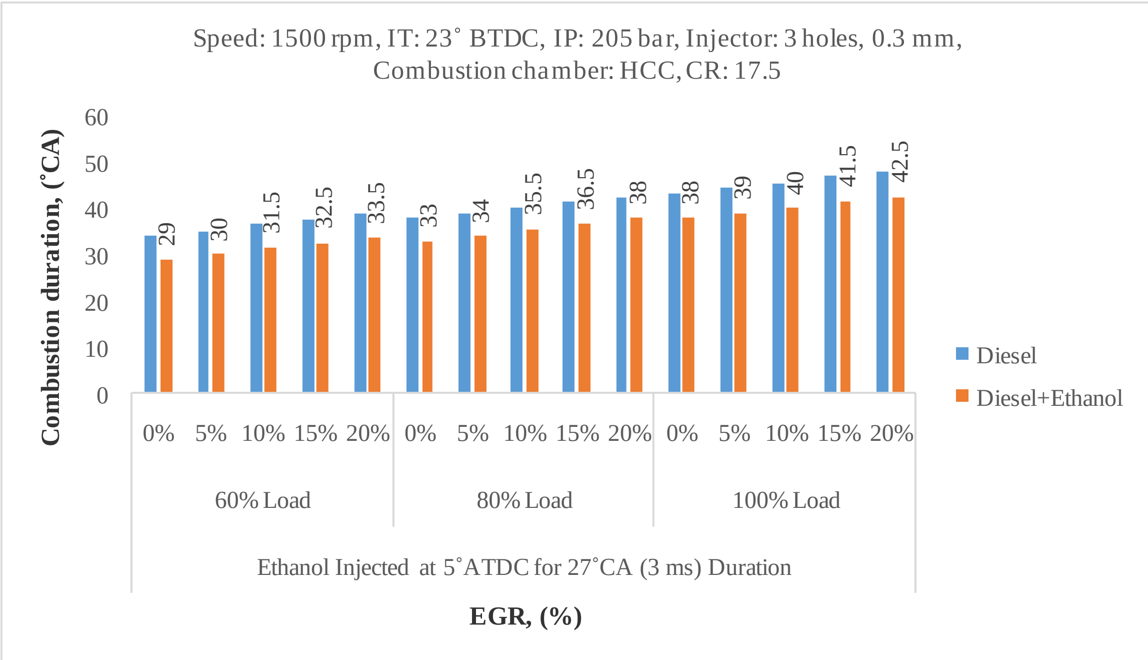


Fig. 3.7 (a) Variation of Combustion duration with the EGR rates for manifold injected ethanol

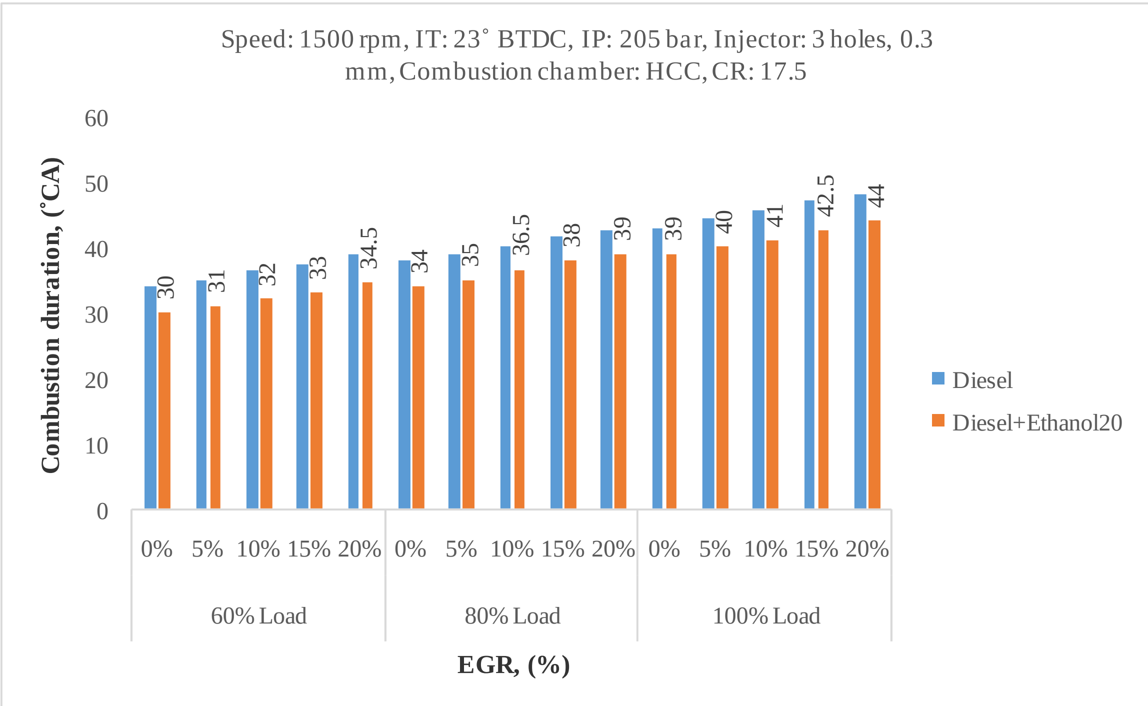


Fig. 3.7 (b) Variation of Combustion duration with the EGR rates for diesel- ethanol blend

3.3.3 Ignition Delay:

Figures 3.8 (a) and (b) presents the variation of ID with different EGR rates for an engine operated with manifold injected ethanol and diesel-ethanol 20 blends respectively. The ID reduced with load and increased with EGR rate at all loads. The EGR supply into the cylinder dilute the charge with carbon dioxide and water vapour that lowers oxygen concentration in the mixture and makes the mixture to act like heat sink which increases the specific heat of the intake charge that reduces the rate of auto ignition reactions that lengthened ID period.

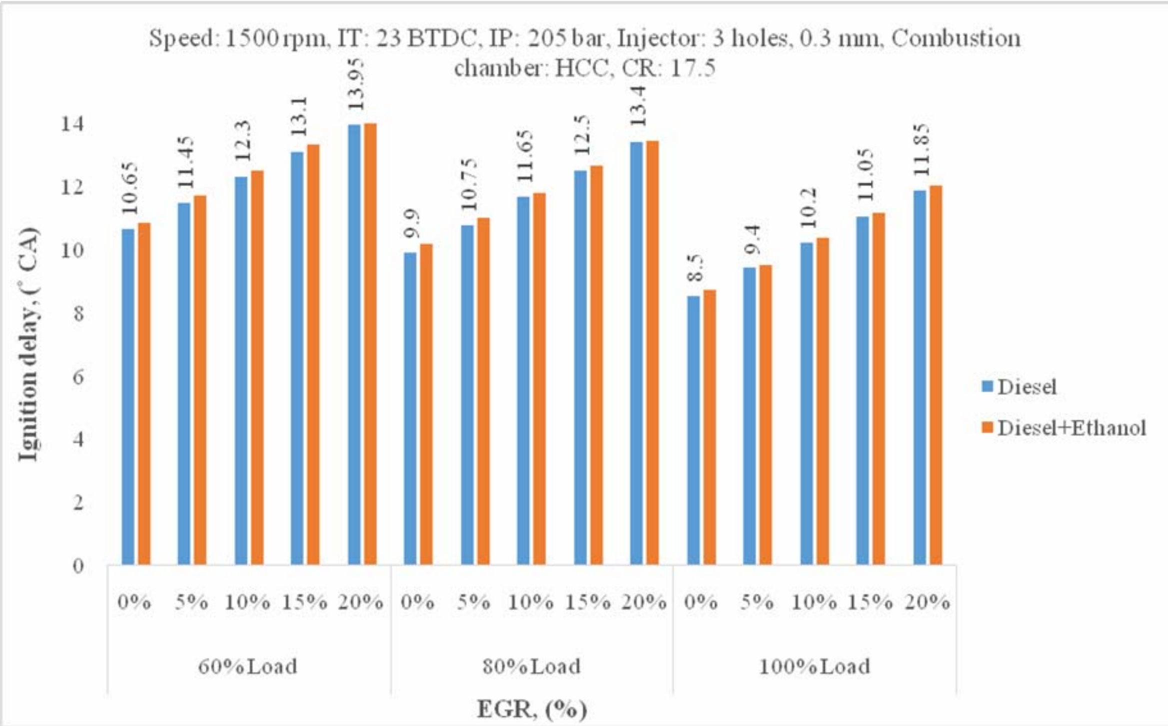


Fig. 3.8 (a) Variation of Ignition delay with the EGR rates for manifold injected ethanol

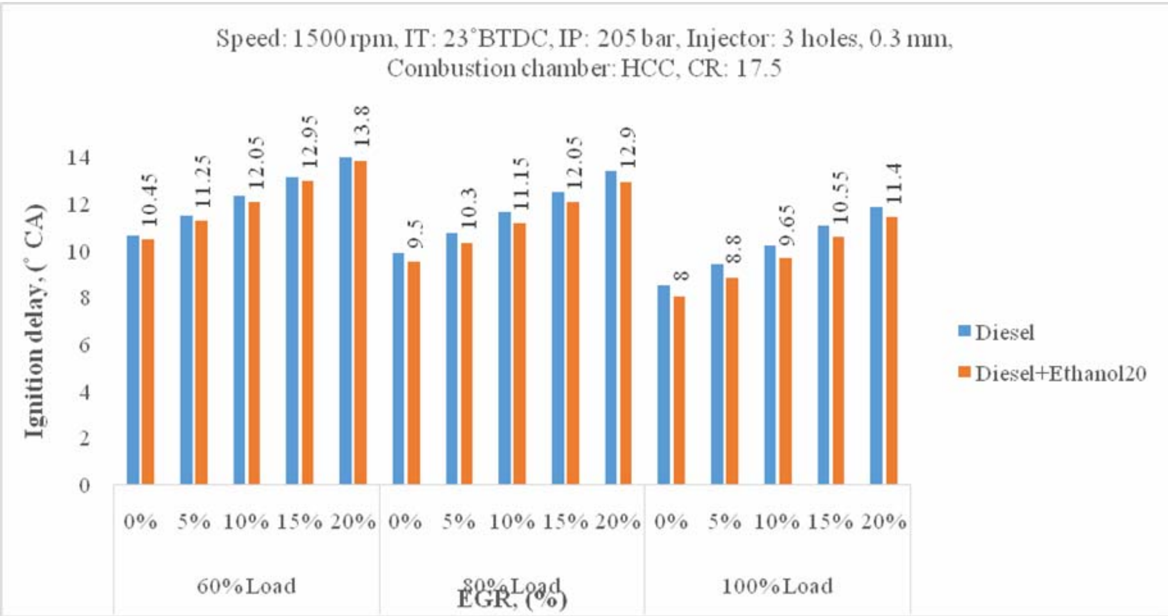


Fig. 3.8 (b) Variation of Ignition delay with the EGR rates for diesel- ethanol blend

3.3.4 Heat ReleaseRrate (HRR):

Figures 3.9 (a) and (b) evidences the variation of heat release rate (HRR) of an engine operated with manifold injected ethanol and diesel-ethanol 20 blends respectively with different EGR rates. It has been observed from the figures that there was a drop in peak HRR for increased EGR percentage. This could be due to the reduction in oxygen concentration in the charge due to the

CO_2 present in the supplied exhaust gas that tend to increase ID that provides more time for the fuel to mix with oxygen.

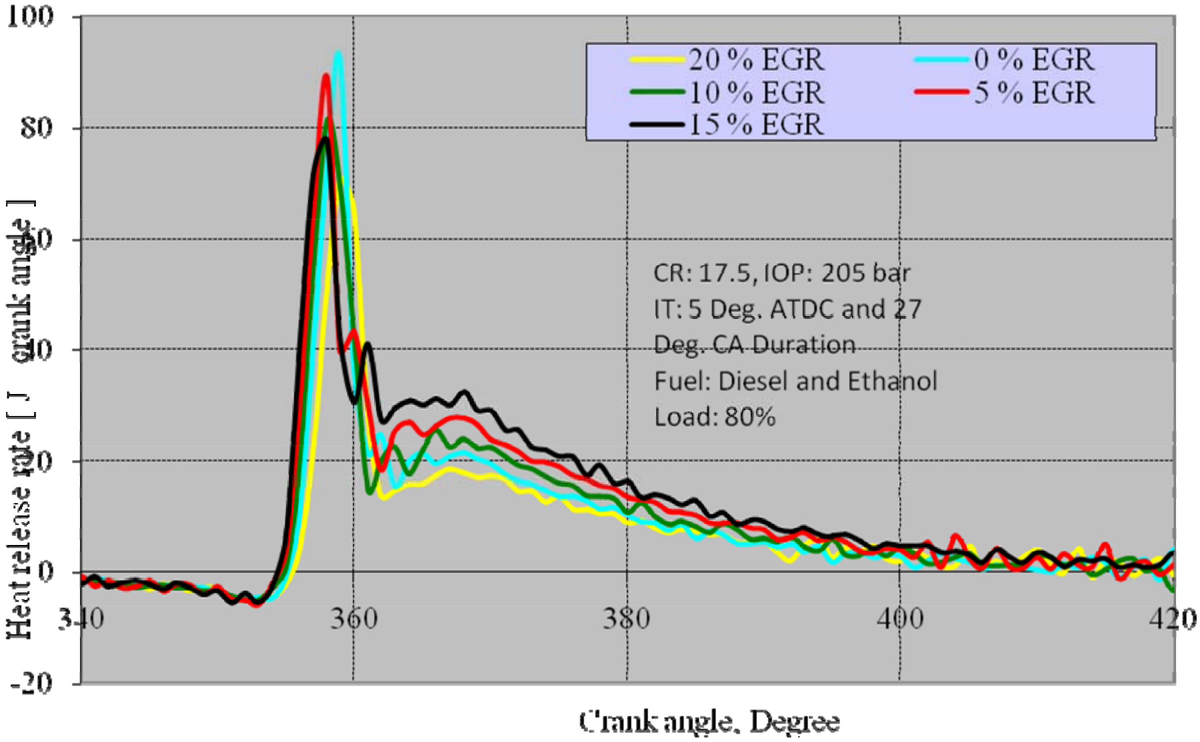


Fig. 3.9 (a) Variation of HRR with CA for different EGR rates for manifold injected ethanol

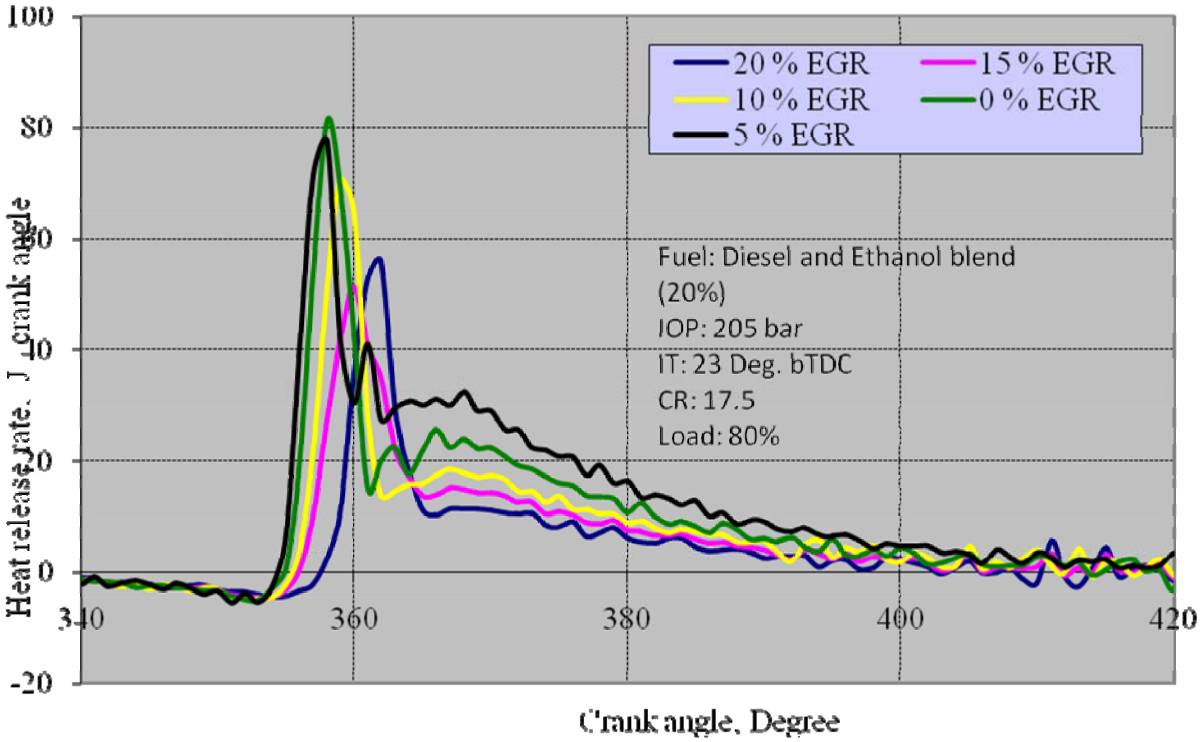


Fig. 3.9 (b) Variation of HRR with CA for different EGR rates for diesel- ethanol blend

4. Conclusions

Experiments were carried out on a single cylinder diesel engine incorporated with an EGR unit, ECU with suitable injector and low pressure fuel pump to inject the ethanol to the intake air in the manifold at 5^o ATDC at injection duration of 27^oCA (3 ms). The 20% ethanol – diesel blend under the same operating conditions were compared to the results obtained with ethanol injection form. The following conclusions were drawn from the comparative experimental work:

- The BTE values decreased slightly with increased EGR rate at all engine loads for both forms studied. Ethanol injection form showed better BTE in comparison with blending form.
- The smoke, HC, CO emissions found increased with increase in EGR rate in both forms studied.
- The smoke emissions were lower in ethanol injection form compared to blending form at all loads.
- The HC and CO emissions were slightly increased in ethanol injection form compared to blending form at all loads.
- The NO emissions were reduced with increased EGR rates. This is because of dilution of the inlet charge due to EGR. The NO emissions were lower in ethanol injection form compared to blending form at all loads.
- The PP reduced marginally with increased EGR rate at all loads. Ethanol injection form showed slightly higher PP compared to other form.
- The ID and CD increases with increase in EGR rate at all loads. The reason for this may be due to dilution of the intake mixture with EGR, which makes the mixture to behave like an inert gas, which does not involve in thermal reaction that led to slows down the combustion speed.
- There was a reduction in peak HRR with increase in EGR rate. This could be due to the reduction in oxygen concentration in the charge due to the CO_2 present in the exhaust gas supplied.

Finally it has been concluded that manifold injection of ethanol at 5˚ATDC with injection duration of 27˚ CA (3 ms) with 10% EGR was found to be optimal for the diesel engine operation with slightly lower BTE, smoke, HC, CO exhaust emissions with same level of NO emission compared to CI mode.

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