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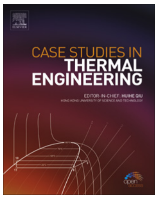

Effect of cooled EGR on modified light duty diesel engine for combustion, performance and emissions under high pressure split injection strategies

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ABSTRACT

Environmental concerns demands light duty Engines to satisfy the stringent Euro VI emission norms. The aim of this study is to present the effect of cooled exhaust gas recirculation (EGR) on emission reduction. Tests are conducted on a modified single cylinder light duty diesel engine to run on high pressure common rail direct fuel injection. Diesel is injected directly in to the engine cylinder for both retarded and split injections at pressures of 200, 230, 250, 300 and 350 bar respectively. Cooled EGR is circulated along with intake air in to the inlet manifold of the engine for flow rates of 5% and 10%(wt/wt) of injected air respectively for both retarded and split injections. Single injection is retarded at − 11° ATDC and split injection consists of pilot injection at − 54°ATDC of 10% mass share and main injection at − 11°ATDC of 90% mass share. The result shows split injection (MPFI) decreases the ignition delay, In-cylinder combustion temperature and peak pressure for higher EGR flow rates compared to retarded single injection (SI) for all Injection pressure. Split injection reduced NO_x from 1400 ppm to 200 ppm for 10% EGR flow rate at 350 bar injection pressure at full load operating conditions. Split injection at high Injection pressure decreases smoke by 10% as compared to retarded single injection. Test results show that there is trade-off exists between retarded and split injections at 350 bar injection pressure at full load conditions. Retarded injection has 33.61% brake thermal efficiency while split injection exhibits only 29.06% for 5% EGR flow rates. But higher EGR flow rates of 10% both retarded and split injection has nearly same brake thermal efficiency of 30.11%. Split injection reduced the combustion duration, ignition delay and exhaust gas temperatures for higher EGR flow rates compared to single retarded injection. The present research reveals that there exists an injection pressure map between the design operating pressure and maximum injection pressure. MPFI system under CRDI mode is very effective in reducing the NO_x emissions with 10% EGR flow rates for maximum Injection pressure. While retarded SI injection is effective for moderate Injection pressure with the same EGR flow rates.

1. Introduction

Globally there is a large concern on environmental pollution due to increase in tremendous vehicular population all over the

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Nomenclature

ATDC	After dead centre
B.P.	Brake power (kW)
bsfc	Brake specific consumption kg/kWh
CAD	Crank angle in degrees
CRDI	Common rail direct injection
EGR	Exhaust gas recirculation
EGT	Exhaust gas temperature
HSU	Hatridge smoke units
MPFI	Multiple split injections
N_2	Nitrogen gas
NO	Nitric oxide
SI	Retarded Single Injection
sfc	Specific fuel consumption kg/h

world. Engine emission mainly depends on fuel quality, injection strategy and engine operating conditions such as speed, load, EGR etc. Portable power generation sets and agriculture light duty a diesel engine contributes significantly for deterioration of ambient air quality. Split injection with exhaust gas recirculation is one of the most prominent and latest techniques applied in diesel engines to reduce NO_x and smoke. EGR can be applied to engines with advanced combustion technology for diesel, biodiesel and gaseous fuels Asad and Zheng and Saleh [1,2]. Earlier reports shown that cooled EGR reduces NO_x effectively compared to hot EGR but regarding brake thermal efficiency hot EGR is better than cold EGR. This is due to the higher intake charge temperature Ishida et al. [3]. Rajesh kumar et al. [4] studied the addition of n-pentanol in diesel fuel in unmodified diesel engine with 45%EGR and reported that NO_x reduced 30% at full load. But however they reported that there is a decrease in thermal efficiency and simultaneously smoke, and HC emissions. They concluded the NO_x and smoke could be simultaneously reduced with moderate EGR rates with small penalty in engine performance. Rajesh Kumar et al. [5] studied combustion characteristics lignin – derived cyclohexanol as a blended in diesel fuel with EGR.They reported that a reduction of 61%NO_x and 14.2% smoke levels with 30%EGR but a further decrease in brake thermal efficiency was noticed due to EGR. Hountalas et al. [6]. Studies conducted on turbocharged heavy duty DI diesel engine for the effect of cooled EGR temperatures for various flow rates revealed low temperature EGR reduced the bsfc and soot but its effect on NOx emissions is limited. Yu et al. [7] examined the effect of various EGR rates, equivalence ratio, flame behavior on thermal efficiency and emissions. They reported that CO concentration decreased when EGR was applied and the EGR ratio was increased as the equivalence ratio neared 1.00. Feng et al. [8] investigated the EGR on low combustion engine and the results showed that there is no change in peak pressure with increase in EGR flow rate and further ignition delay increased with decrease in initial boiling point. Verschaeren et al. [9] studied the combination of EGR and early valve timing in medium speed turbo charged diesel modified diesel engine with two cam shaft configurations. They reported that greatest NO_x was achieved and concluded that trade-off between UHC and NO_x was greatly reduced. Also PM emissions are much reduced over the entire load region due to higher volumetric efficiency. EGR can also be applied to diesel Engine run on fuel prepared from reprocessed plastic waste by Mani et al. [10] studied the effect of cooled EGR on single cylinder DI diesel engine run on waste plastic oil and reported that cooled EGR reduced the combustion peak temperatures and NO_x with 20% EGR, however there is an increase in smoke levels due to the waste plastic oil. EGR inhomogeneous charge compression ignition engine (HCCI) combustion is another technique to reduce the NO_x emissions. Miller Jothi et al. [11] experimentally investigated HCCI with 100% gaseous fuel LPG and reported that brake thermal efficiency increases at part loads for all percentages of EGR but at full load higher flow rates of EGR affects the brake thermal efficiency. The effect of early pilot injection with exhaust gas recirculation in HCCI direct injection heavy duty diesel engine was investigated by Fang et al. [12]. They reported that NO_x emissions decreased with increase in pilot fuel quantity and suggested that low level of EGR is effective method in reducing NO_xemissions Engelmayer et al. [13] conducted test runs on a single cylinder medium speed research engine delivering power at 300 kW with high pressure multiple injections and cooled EGR. They studied the spray characteristics, combustion, soot and the extent of high pressure injection. The results concludes that soot emissions can be lowered effectively both at part and full loads with high pressure injections with sophisticated EGR system. Common rail direct injection with multiple injections with or without separation is widely used in passenger cars due to the increase in demand for higher torque, specific power output and reduce fuel consumption and emissions. For this fuel injection equipment (FIP) was developed by Delphi diesel systems. This fuel injection system can inject the fuel at high pressure and the time separation between two injections can be reduced to 0 micro seconds. With this injector diffused combustion was avoided and minimum NO_x were achieved with EGR. However early injection with EGR resulted higher HC emissions due to lean combustion and lower combustion temperatures Dober et al. [14]. Lee et al. [15] investigated the effect of EGR on pilot injection with 14holes multi hole injector under idling conditions and noticed that significant increase in power output with simultaneous reduction in PM and NO_x. Low temperature exhaust gas recirculation will handle higher mass of exhaust gas due to the less volume occupied by it. This will create more space for fresh air so that the engine can digest more EGR compared to high temperature EGR. Mehrotra et al. [16] tested low temperature exhaust gas in sports utility vehicle (SUV) and reported that engine can take higher amount of air so that more heat can be supplied by EGR process. The results shows that for the same amount of fuel with low temperature exhaust gas around 16.4% reduction in NO_x and 23.3% lower PM was achieved. Similar results are also reported by Brijesh et al. [17] that ultra-cooled EGR with retarded injection increased thermal efficiency, reduced NO_x and PM but higher HC and CO even with low pressure injection. The effect of PCCI combustion with EGR was studied by Cheng et al. [18] and reported that advancing pilot injection resulted the in-cylinder peak pressure, ignition delay was shortened,NO_x PM and soot emissions reduced but there is an increase in HC emissions. Sarangi et al. [19] investigated 50% of pilot and main injection with high flow rate of EGR in single cylinder high speed DI diesel engine. The result shows that the combined effect of split injection and EGR requires less amount of EGR as compared to single injection and also NO_x can be reduced to zero level with significant brake thermal efficiency. This technique-reduced smoke by 17% compared to single retarded injection. High pressure split injections consisting of 6 injections per cycle in AVL single cylinder DI diesel engine with electronically controlled injections of pressure up to

200 MPa was studied by Yang et al. [20]. Their findings show that up to 100 MPa the combustion is faster due to which the in cylinder gas temperature is high compared to convention allow-pressure fuel injection. Yin et al. [21] optimized the split injection and EGR at various high-pressure injections noticed that to reduce NO_x and soot emissions high levels of EGR is required for late injection when split injection is not incorporated. At high Injection pressure NOx increased slightly soot initially decreased sharply an increase in bsfc was noticed. However with split injection with minimum quantity of pilot injection in late injection improved the brake specific fuel consumption. Numerical simulations conducted by Wang et al. [22] showed that 5 split injections without EGR is more effective than 3 split and single injections. At the same time with EGR there is no much variation of NO_x either with 5 or 3 split injections. Han et al. [23] made numerical simulations using kiva-II code and confirmed that multiple injections reduce NO_x similar to that of a single injection with injection timing is retarded. At the same time significant amount of soot is reduced without effecting much NO_x emissions. Reactivity controlled compression ignition (RCCI) was investigated by Wu and Reitz [24] at high loads with EGR and boost pressure using computational fluid dynamics (CFD). They found that CO, HC and soot are highly sensitive to EGR variation in late injections. Combustion and emissions are improved and the sensitiveness of EGR reduced with increase in injection pressure. Experimental conducted by Roy et al. [25] on single cylinder diesel engine modified to CRDI and EGR analyzing the experimental results using grey-fuzzy taguchi approach concluded that EGR is the most influencing parameter on engine emissions.

Limited research was available on the combined influence of ultra cooled EGR and split injections on single cylinder low duty diesel engine under high and low load operating conditions. Hence in the present work intensive experiments are conducted on modified single cylinder low duty high speed engine of 3.5 kW power at 1500 rpm running speed using CRDI system. The fuel injection system was modified to CRDI capable of injecting precise quantity and timing controlled by external programmable electronic controller. The injection system is capable of injecting the fuel at very high pressures up to1000 bar. The split injection consists of 10% of the fuel injected during pilot injection at − 54CAD and remaining 90% fuel injected at main injection at − 11CAD with two ultra cooled EGR flow rates of 5% and 10%

2. Experiment set up and methodology

Experiment Test Rig of high-pressure multiple split injection engine test rig with exhaust gas recirculation facility.

The engine used in this experimentation was a Kirloskar make single cylinder direct injection diesel engine delivers 3.5 kW at 1500 rpm with specifications mentioned in the Table 1. The engine is coupled to dynamometer of capacity 3.5 kW supplied by Powermag India Ltd. The combustion pressure was measured by air cooled kistler make pressure sensor. A charge amplifier is connected to the sensor by high temperature cable. The engine is fitted with variable injection timing kit which consists of all the components of CRDI and electronic injection controller is provided to control the injection timing and quantity. The fuel supply system consists of low and high-pressure circuits, which maintain constant and unvarying pressure. The high-pressure pump is run by 5 H.P. electric motor. The fuel pressure is controlled by a control valve operated by a electromagnet solenoid valve. The fuel rail pressure is fitted with a pressure sensor and a pressure relief valve is provided for safety against high-pressure build up in the rail. The mechanical injector was replaced by electro magnet system in which the solenoid armature does not control the pintle but by the movement of a small rotating ball, which regulates the fuel flow from a valve control chamber within the injector. A crankshaft position sensor typically sends the data to the electronic control unit (ECU). This electronic control unit was a pre-programmed microcontroller used to signal start of injection and duration. This microcontroller was connected to the PC hardware by taking the

Table 1
Engine specifications of the modified single cylinder diesel high pressure fuel injection test rig.

Sl. no.	Parameter	Specification
1	Make	Kirloskar
2	Model	AV1
3	Type	Single cylinder, 4 Stroke, Direct Injection, Water cooled CI Engine
4	Rated Power	3.7 kW@1500 rpm
5	Engine speed	1500 rpm
6	Fuel	Diesel
7	Bore & Stroke	80 × 110 mm
8	Displacement	$553E-6\ m^3$
9	Compression Ratio	16.5:1, Range: 13.51–20
10	Injection Pressure	200–350 bar
11	Cylinder Pressure	Piezo Sensor, Range: 200 psi
12	Nozzle	1 hole, Ø0.0020 m
13	Dynamometer	Eddy current dynamometer
14	Orifice Diameter	20 mm

input signal from the crankshaft position encoder. Thus the electronic fuel injector is controlled by ECU. Ultra cooled EGR is circulated in the engine by tapping the exhaust gases in the main exhaust line through a stepper motor control valve and passed through a cooler. To know the mass flow rate of EGR a digital manometer is provided at the inlet manifold of the engine.

3. Experiment method

Experimentation was conducted on a standard single cylinder, 4 stoke DI diesel engine with rated power of 3.7 kW. The specifications of the engine used for experimentation are detailed as tabulated in Table 1. Engine speed, intake air, cooling water flow rates and EGR temperature were maintained constant throughout the experimentation. The detailed experimental setup is as sketched in Figs. 1a and 1b. Eddy current dynamometer was connected to the engine to apply load on the engine in the steps of 0.5 kW. The engine emissions such as CO, CO_2, O_2, HC & NO_x were measured by Mars multi gas analyzer while smoke opacity was measured by Indus smoke meter approved by Automotive research association of India (ARAI). Gas analyzer was calibrated with syngas consisting of CO in N_2 10%, CO_2 in N_2 5% and NO_2 in N_2 2000 ppm. The 5 gas analyzer is checked for O_2 sensor showing 20.9% while the remaining emission readings are zero at room temperature. Otherwise, the instrument must be checked for any HC residue left in the instrument. The instrument must be exposed to the exhaust gases at least for 5 min to warm up before taking the reading. Initially, the engine was run on neat diesel, performance and emission parameters were recorded by varying load from 0.5 to 2.8 kW. During phase-I of experimentation, engine was run on neat diesel on retarded single retarded injection at − 11CAD without EGR and fuel Injection pressure are varied from 200,250,300 and 350 bar respectively. During the phase –II of experimentation two EGR flow rates of 5% and 10% respectively was circulated for the same retarded injection angle for the above pressures respectively. Then during the phase –III of experimentation two split injections at angles of − 54CAD and − 11CAD was chosen whose mass share for pilot injection is 10% and main injection of 90% was chosen and experimentation was conducted as per the above mentioned Injection pressure and EGR flow rates. Throughout the experimentation, Engine was run at constant speed of 1500 rpm. The engine was allowed to reach steady state condition before recording the parameters. All sets of reading were taken when engine is running on current experimentation fuel and necessary care has been taken that no fuel from previous experimentation was left out in the engine diesel oil filter. Every set of experimentation was repeated for three times and mean readings were recorded. At each load performance characteristics (BTE) and emissions smoke opacity were recorded and evaluated. Before each experiment, emission analyzer filters were changed and engine was allowed to cool to room temperature.

4. Uncertainty analysis

The accuracy of experiment results mostly depends on uncertainty analysis. Several factors contribute the uncertainty during experimentation such as observation, environment and instrument type. Before taking the reading for each load the engine is run for at least 30 min time and there is no much variation in cooling water temperature. Engine data is collected for each load at least 3 times and graphs are plotted by taking the average values. The measuring range and accuracies of measurable parameters were represented in the Table 2. Uncertainty analysis was conducted for engine performance, emissions and smoke measurable parameters based on analysis by Roy et al.,2014 and Holman, 2012 [26,27] are presented in Tables 3 and 4. Detailed calculations are shown in Appendix A. It is found that the uncertainties measurable and computed parameters for experimentation with 95% confidence level at 350 bar injection pressure for split injection @10%EGR is range between 0.5% and 1.92%

5. Results and discussion

In exhaust recirculation with ultra cooled EGR the engine is run at constant speed varying fuel injection angle and pressures throughout the experiment and the results are compared with neat diesel engine operation without EGR. Combustion parameters like

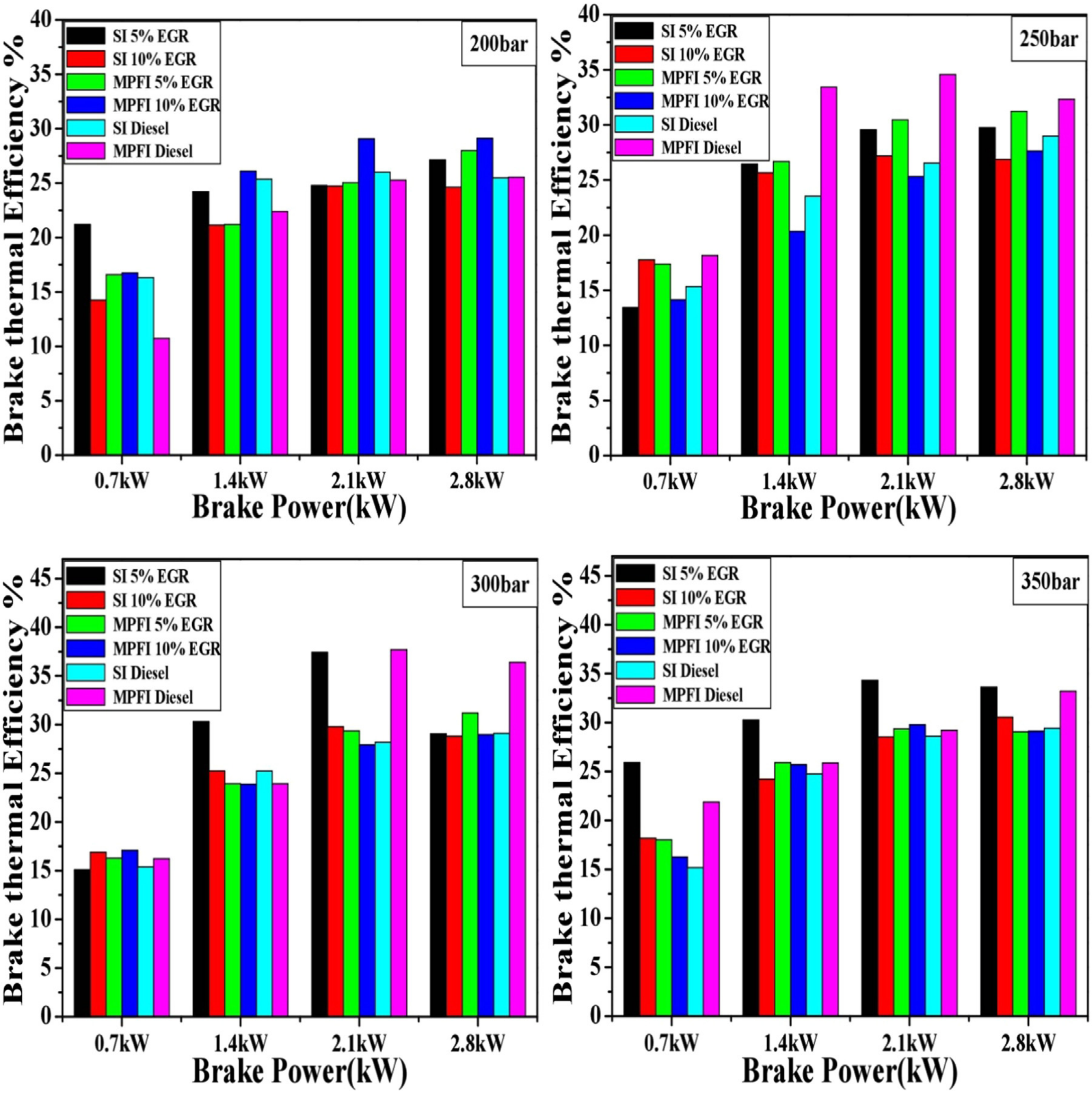

Fig. 1. Brake thermal efficiency of SI and MPFI diesel combustion at varying injection presssures for at different EGR conditions.

Table 2
The measuring range and accuracy of measurable parameters.

Measured qty.	Measuring range	Accuracy
Speed	0–2000 rpm	± 1 rpm
Specific fuel consumption	0–3 kg/h	0.001 kg/h
Exhaust gas temperature	30–1000 °C	± 1 °C
Smoke opacity	1–100 HSU	± 0.1 HSU
NO_x	0–2000 ppm	± 1 ppm
Load	0–2.8 kW	± 0.01 kW
Torque	0–30 Nm	0.01 Nm
In -cylinder Gas Temperature	20–2000 °C	0.01 °C
Ignition Delay	0–20 deg CA	0.1 deg CA
Peak Pressure	1–200 bar	0.01 bar
Average combustion Duration (deg CA)	0–100 deg CA	0.1 deg CA
Averaged maximum rate of cylinder pressure rise	0–10 bar/deg	0.01 bar/deg
Averaged maximum rate of heat release	0–100 J/deg	0.01 J/deg
Crank Angle	0–360°	0.1°

Table 3
Sample calculation of total uncertainty (%) in measurement of various measurable parameters at 2.8 kW load for 350 bar injection pressure for split injection @10%EGR.

Measured parameter	Test-1	Test-2	Test-3	Mean = $\overline{X}$	Variable Error with 95% confidence level = 2σ	$\%U_{.95} = \frac{2\sigma * 100}{\overline{X}}$	% Fixed Error of Instrument (FEI)	$\%TotalUncertainty\,inmeasurement\,(TU) = \sqrt{U_{.95}{}^{2} + FEI^{2}}$
SFC	0.268	0.269	0.27	0.27	0.002	0.607	0.5	0.79
Torque	17.95	18.33	18.14	18.14	0.310	1.710	0.1	1.71
Ignition Delay	5.25	5.37	5.34	5.32	0.102	1.917	0.1	1.92
Peak Pressure	48.5	49.5	49	49.00	0.816	1.666	0.1	1.67
Averaged maximum rate of cylinder pressure rise	1.41	1.4	1.4	1.40	0.009	0.672	0.3	0.74
Averaged maximum rate of heat release	20.2	19.99	20.05	20.08	0.177	0.880	0.2	0.90
NO_X (ppm)	240	239	239	239.33	0.943	0.394	0.3	0.50
Smoke Opacity ((HSU)	80.79	80.9	80.5	80.73	0.337	0.418	0.4	0.58

Table 4
Total uncertainty (%) in performance parameters and their relevant measurable parameters at 2.8 kW load for 350 bar injection pressure for split injection @10%EGR.

Parameter	Variable	Uncertainty in measurement or computation
Brake Power	Torque, Speed	1.68%
BSFC	Brake Power, SFC	0.79%
BTE	Brake Power, SFC	0.57%

in cylinder gas temperature, rate of heat release, igntion delay are measured with respect to crank angle and the emission parameters such as NO_x are measured and compared to that of neat diesel operation.

5.1. Brake thermal effeciency

The effect of exhaust gas recirculation on brake thermal effeciency for single and split injections for Injection pressure ranging from 200 bar to 350 bar at different loads are shown in Fig. 1. The brake thermal effeciency increases with increase in injection pressure. Higher EGR flow rates decreased the brake thermal efficiency marginally for both single retarded and split injections. This reduction in brake thermal effeciency is due to the decrease in availability of oxygen for combustion process because of oxygen replacement with higher percentages of EGR. EGR decreases excess air fuel ratio due to the replacement of air leading to deteriorated combustion and there by a decrease in brake thermal effeciency. The obtained results are in accordance with the earlier results reported by Mani et al. [28]. At low EGR flow rates,single retarded injection has higher brake thermal effeciency compared to split injections. However the experimental results shows that without EGR split injection has higher brake thermal efficiency than single retarded injection for all Injection pressure. At moderate loads for higher EGR flow rates retarted single injection is exhibiting better brake thermal effeciency compared to split injections as can be seen in Fig. 1. But when the engine is operating at full load condition for 10%EGR flow rates both retarded and split injections are exhibiting equal brake thermal effeciency of 30.1% at 350 bar injection pressure. This shows that for higher EGR flow rates there is no much variation in brake thermal effeciency either for retarded and split injections. From the graphs it is noted that split injection with 5%EGR flow rate has maximum thermal efficiency of 29.06% while SI system exhibits 33.61%brake thermal efficiency at 350 bar injection pressure. This shows that MPFI system exhibits marginal decrease in brake thermal effeciency compared to SI injection.better performance compared to single injection. Hence the present work reveals that lower EGR flow rates is suitable for multiple injections that single retarded injection for higher pressure injection system.

5.2. Peak pressure

The variation of peak pressure with respect to crank angle at full load conditons are shown in Fig. 2. The experimental results shows that increase in EGR flow rates decreased the peak pressure during the combusiton. Simultaneously peak pressure occurance also advanced with increase in injection pressure. The results shows that as the Injection pressure are increased MPFI has developed more peak pressure compared to SI injection for all Injection pressure as seen in Fig. 2. Results shows that for SI injection peak pressures increases with increase in loads. For higher EGR flow rates SI injection reduced the peak pressures confirming that higher EGR flow rates for both SI and Multiple injections is an effective method in reducing the peak pressures. However higher EGR flow rates could deteoriate the lub oil condition and increase in soot formation. Fig. 2 shows that there is an increase in peak pressure when the engine load increases at different Injection pressure for both SI and Multiple injections. Increase in Injection pressure also increases the peak pressures for both SI and multiple injections for all EGR flow rates. However MPFI injection with out EGR circulation recorded higher peak pressures as compared to SI injection. EGR circulation reduced the peak pressures for both SI and multiple injections.

Results show that for 10%EGR flow rate for multiple injections at full load conditions reduced the peak pressure by an amount of 14.2% as compared to without EGR.This may be attributed due to decrease in combustion temperature in presence of cooled EGR with multiple injections. Fig. 2 show that For SI injection peak pressures decreased from 52.7 bar to 49.34 bar while for MPFI system it is from 54.13 bar to 52.07 bar at full load and 350 bar Injection pressure when EGR flow rates increased from 5% to 10%. SI injection with 10% EGR flow rates decreased the peak pressure to 48 bar compared to 51 bar with 5%EGR flow rates at higher Injection pressure. Higher EGR flow rates was able to reduce the combustion peak pressures by 5.8%. For SI 10% the peak pressure occurance is at 45.74°ATDC while for MPFI it is 48.13°ATDC. This shows that MPFI injection the peak pressure has advanced more comparatively to that of SI injection. At the same time increase in Injection pressure advanced peak pressure occurance. For MPFI 10% occurance of Peak pressure is advanced from 48.13° to 51.87° while for 10%SI injection it is from 45.74° to 49.39°ATDC when the Injection pressure increases from 200 bar to 350 bar at full load conditions. Similar results are also noted for all Injection pressure for different EGR flow rates to both SI and MPFI injection strategies. Hence It can be concluded that Multiple injection strategy with high EGR flow rates is effective in reducing the combustion peak pressure for all Injection pressure compared to SI injections.

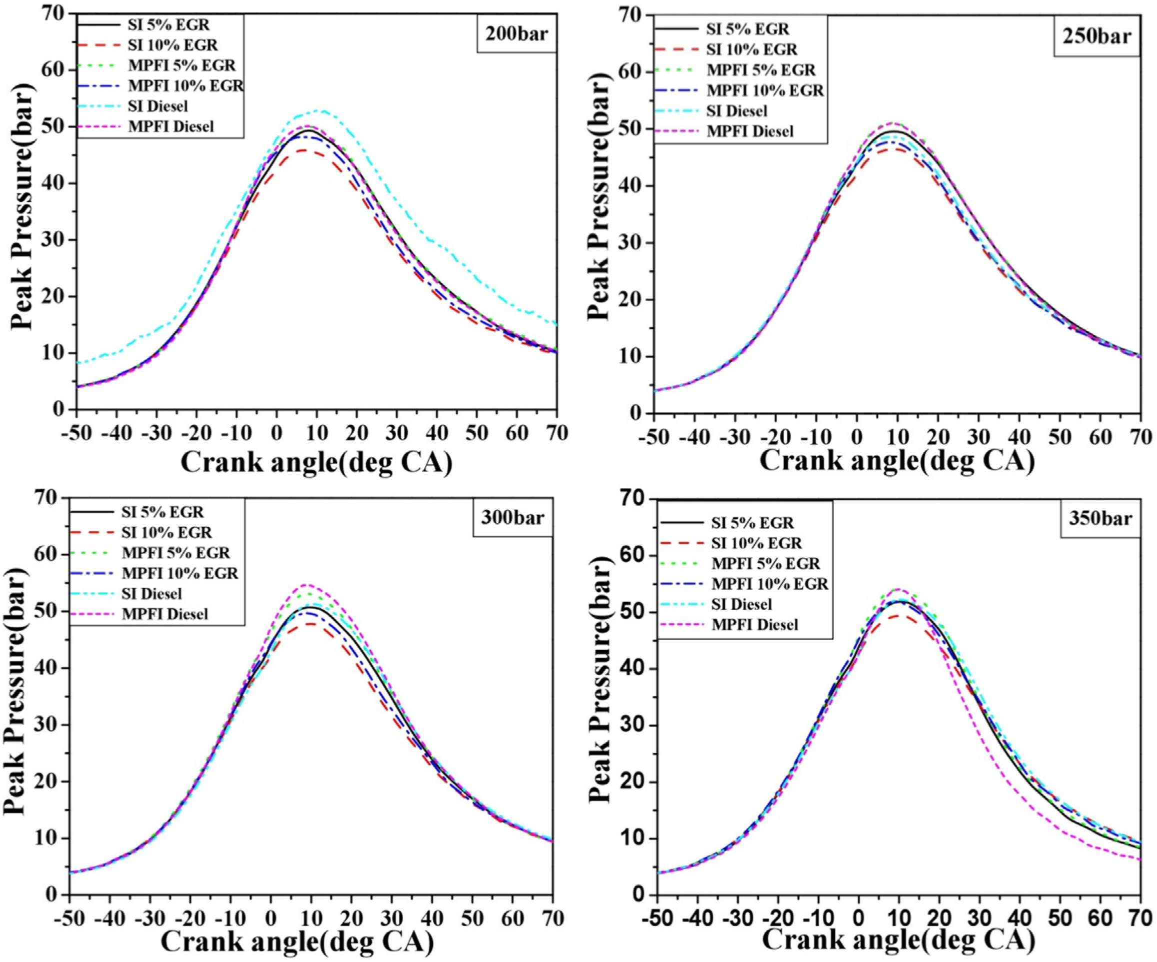

Fig. 2. In cylinder pressure variation of SI and MPFI diesel combustion at varying injection presssures for at different EGR conditions.

5.3. Ignition delay

The data presented for ignition delay relative to engine load at various different Injection pressure are shown in Fig. 3. The variation of ignition delay for retarded SI at − 11° BTDC and multiple injections at − 54° and − 11° BTDC for both 5% and 10%EGR are represented in these Fig. 3. It can be seen that increase in Injection pressure has marginal effect on ignition delay for both SI and multiple injections without EGR. Increase in Injection pressure does not change the ignition delay significantly for all engine loads for both SI and multiple injections without EGR circulation. Similar results are reported by Cowart et al. [29]. Experiment results show that increase in injection pressure decreased the ignition delay for SI injection up to 300 bar without EGR. However when the injection pressure increased to higher values of 350 bar there is an increase in ignition delay from 3.45° to 3.85° for 5%SI while for 10% SI ignition delay increased from 5.15° to 5.35° as shown in Fig. 3. Higher EGR flow rates increased the ignition delay for SI injection for all Injection pressure. This is due to the less availability of air and decrease in temperature at SOI due to the higher percentage of cooled EGR. It can be seen that multiple injections with EGR reduced the ignition delay compared to SI injection with EGR for all Injection pressure ranging from 200 bar to 350 bar. 10% MPFI has lowest ignition delay of 2.4° compared to 5.15° for 5% SI at 300 bar injection pressure and full load engine operating conditions. This can be attributed to the improvement in combustion process and equivalence ratios. Multiple injections without EGR have different effect on ignition delay when compared to SI injection. Increase in Injection pressure from 200 bar to 350 bar for multiple injections without EGR shows that there is an increase in ignition delay 0.9–4.05° as seen in Fig. 3. This behavior is quite opposite to the earlier results reported with SI injection. EGR has positive effect on multiple injections for increase in Injection pressure as one can see that the ignition delay decreased with EGR circulation. This is due to the decrease in chemical delay since the SOI injection is fixed and also the engine speed is kept constant at 1500 rpm.

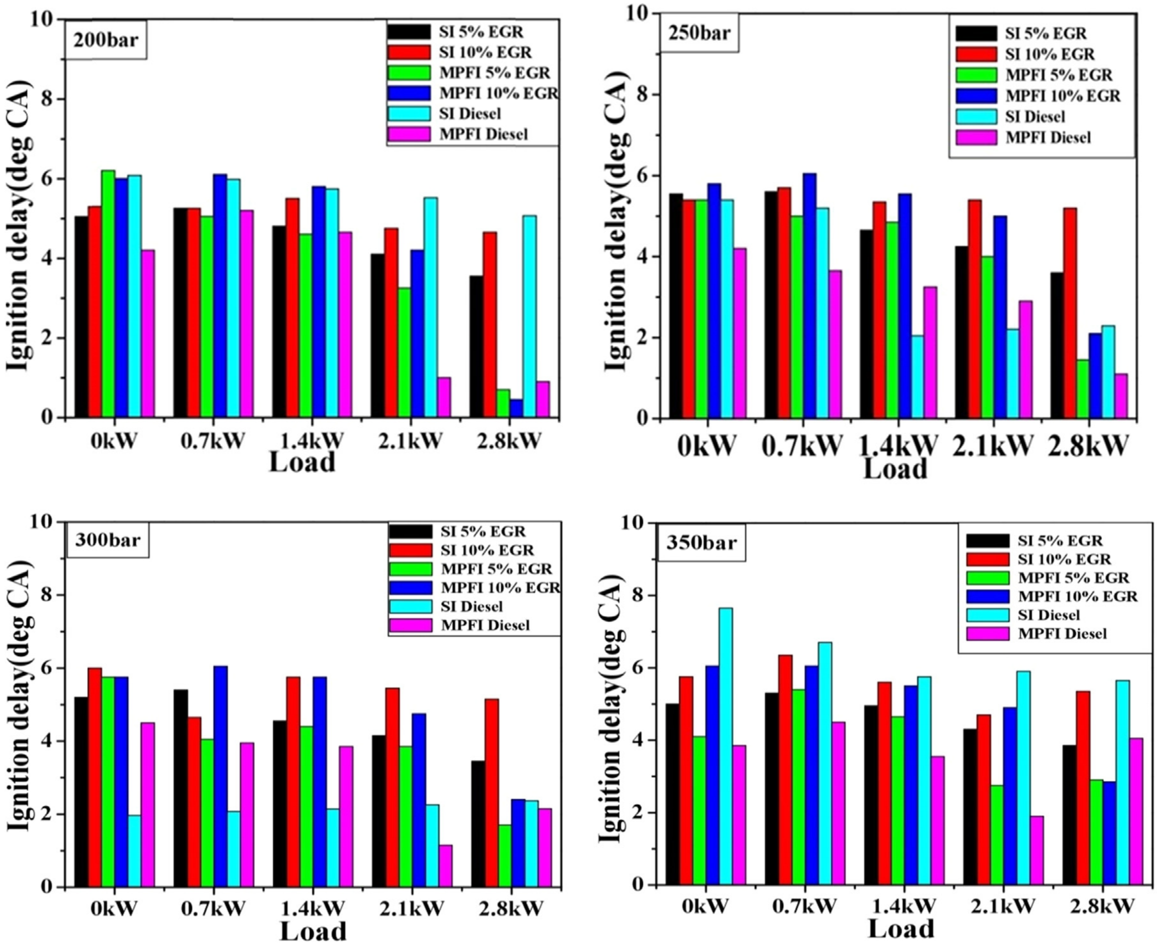

Fig. 3. variation of Ignition delay of SI and MPFI diesel combustion at varying injection presssures for at different EGR conditions.

5.4. Heat release rate

Heat release rate is one of the important characteristic to study the combustion process in high pressure multiple injections with EGR circulation. Several peaks can be seen in HRR graphs in Fig. 4. EGR is used to reduce the higher peak values of HRR in high pressure multiple injection with advanced fuel injection strategies. MPFI heat release rate curves has 4 peaks showing the small peaks at − 38° and − 11° fuel injections while the remaining two high secondary peaks shows the low temperature and high temperature zones. In multiple injection the pilot fuel is injected at − 54° BTDC but the SOC is initiated at − 38° at high injection pressure of 350 bar. This retarded SOC is due to the EGR circulation. Similar results are also reported in HCCI combustion using biodiesel with external mixture formation technique Singh et al. [30]. This delay can be attributed to chemical delay. Retarted injection without EGR has highest HRR peak as seen in all Fig. 4. But EGR circulation reduced the peak HRR value and also the occurrence of HRR is shifted towards BTDC.This is due to the decrease in cylinder temperature and decrease in combustion rate. MPFI fuel injection reduced the peak value of HRR compared to single retarded injection showing that MPFI technique at high pressure injection is an effective tool in reducing the peak value of HRR.peak value of HRR is decreased from 19.38 J/deg at 300 bar is reduced to 18.61 J/deg at 350 bar. Similarly HRR value is decreased from 20.07 J/deg at 300 bar to 19.50 Jdeg at 350 bar for 5%SI retarded injection. Similar results are also observed for all EGR flow rates for both SI and MPFI strategies. Thus High pressure MPFI technique is an effective tool to control the combustion rate and improves the combustion process and safety of the engine structure when operated at high pressure fuel injection. High EGR flow rates reduced the HRR for both SI and MPFI techniques. This is due to absorbing large amount of heat released during combustion by the non reactive mixture components in the cold EGR Nakano et al. [31]. Higher EGR flow rates improved the premixed combustion and decreased the diffusion combustion as seen in above figs. Similar results are also reported in earlier discussion in combustion duration as seen in Fig. 4. Hence the combustion duration decreases with increase in EGR percentages for high pressure fuel injections. As a result 10% EGR has different HRR compared to 5%EGR for both retarted and multiple injections. Trade-off results are noticed for HRR value with 5%EGR and without EGR for both multiple and split injections. Without EGR 0% SI has 28.44 J/deg while MPFI has less HRR value of 22.67 J/deg at 300 bar full load operating conditions. While at the same time 5% SI has HRR value of 20.07 J/deg while 5%MPFI has HRR 19.38 J/deg at 300 bar. Interestingly the results show that

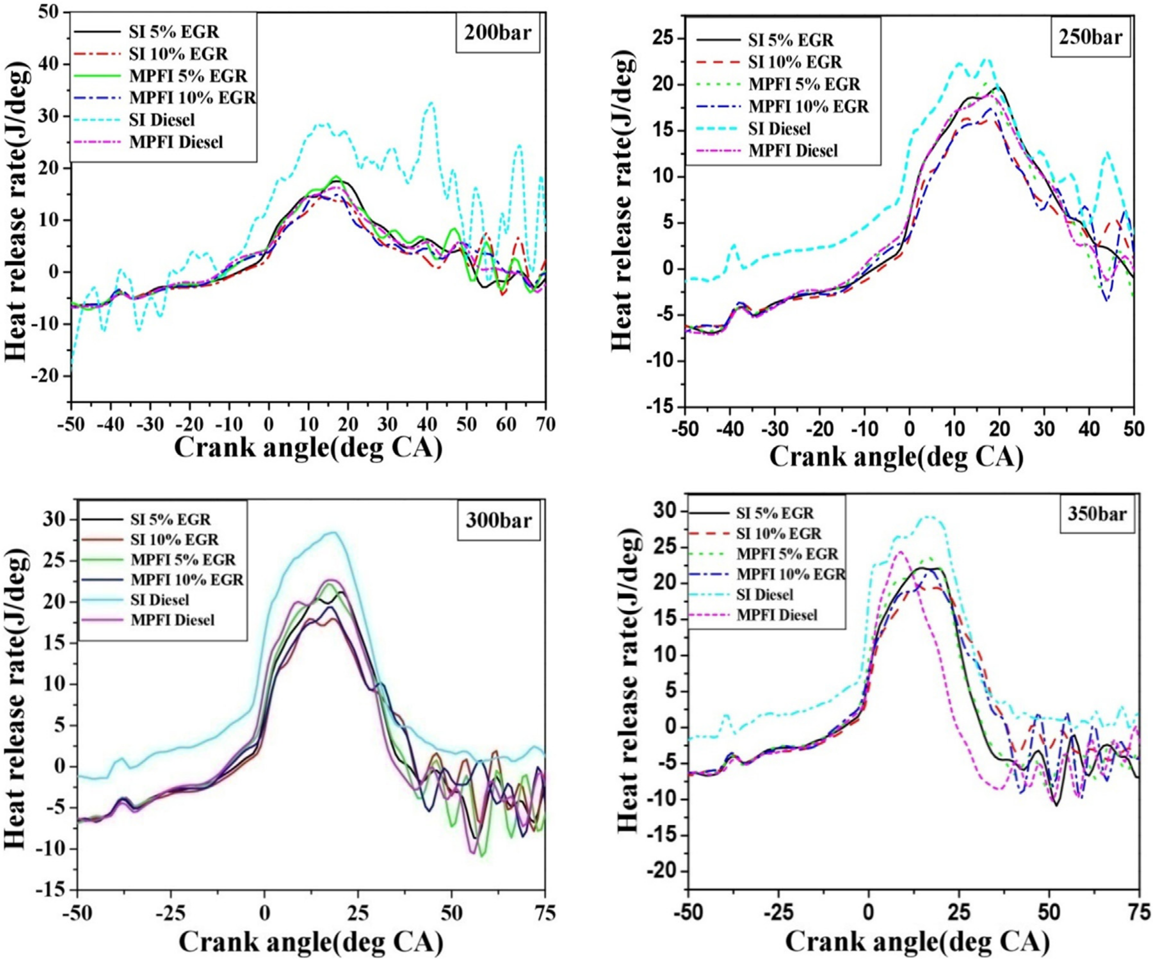

Fig. 4. Heat release rate of SI and MPFI diesel combustion at varying injection presssures for at different EGR conditions.

beyond 300 bar injection pressure i.e. at 350 bar MPFI has HRR value of 20.66 J/deg while 5%SI has only 19.50 J/deg. Thus it can be concluded that MPFI with all EGR flow rates has delivered higher HRR values at high Injection pressure of 350 bar while SI retarded injection is most suitable for 5%EGR upto 300 bar.

5.5. In cylinder gas temperature

In Fig. 5 shows the variation of incylinder gas temperature for no load and full load engine operating conditions. It can be seen that incylinder gas temperature increases with increase in engine load due to the increase in fuel quantity. EGR percentage and fuel Injection pressure are the two important parameters which effect the incylinder gas temperature. It can be seen that EGR increased the incylinder gas temperature for both SI and MPFI injections for all Injection pressure ranging from 200 bar to 350bars. Incylinder gas temperature increased from 1497 °C to 1591 °C when the EGR flow rate is increased from 0% to 10% for MPFI injections. Similarly for SI injection also the incylinder gas temperature increased from 1550 °C to 1602 °C. This is due to the increase in igntion delay due to the EGR circulation. However the incylinder gas temperature can be reduced by increasing the EGR percentages as seen in Fig. 5. There is 7.8% decrease in incylinder gas temperture when the EGR flow rate is increased by 5% for both SI and MPFI systems. This is due to the charge dilution and less intense incylinder conditons such as less oxygen availability, decrease in chemical reaction rate, increase in specific heat of reactant mixture. Similar results are also reported in HCCI engine fueled with natural gas and diesel by Jafarmadar et al. [32].

5.6. Smoke emissions (HSU)

Fig. 6 shows the variation of smoke of diesel fuel at different Injection pressure with EGR for SI and MPFI combustion. Low smoke is another advantage for MPFI compared to SI combustion mode. Particulate matter and soot can be assessed by the amount of smoke released in the exhaust. Smoke is measured by the Indus diesel smoke meter in this experiment work. The intensity of smoke

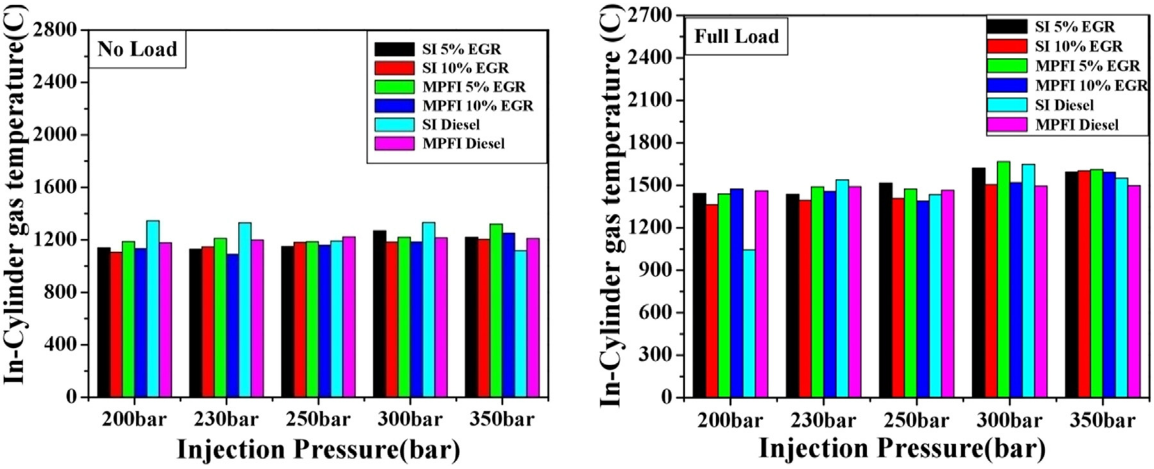

Fig. 5. Incylinder gas temperature of SI and MPFI diesel combustion at varying injection presssures for at different EGR conditions.

increased with increase in the amount of EGR circulated for both SI and MPFI combustion mode. The increase in smoke is due to the increase in non-homogeneous mixture due to the EGR circulation which leads to heterogeneous combustion. Heterogeneous combustion is responsible to increase the carbonaceous particles in the exhaust which increases the smoke due to the fuel enrichment during the combustion to the keep the engine speed constant at 1500 rpm B. Rajesh Kumar et al. [33]. Results show that increase in engine load increases the smoke as seen in Fig. 6. For 0%MPFI smoke levels increased from 43HSU to 56.1HSU while with the EGR circulation 10%MPFI smoke levels increased from 55.5HSU to 70.6HSU at 350 bar injection pressure when the load increased from no load to full load engine operating conditions. However the rate of increase of smoke is higher for MPFI as compared to SI combustion mode for moderate Injection pressure up to 300 bar. Significantly Higher Injection pressure of 350 bar released less amount of smoke compared to SI mode at full load conditions with 10%EGR. SI combustion releases smoke of 80.8HSU where as MPFI released only 70.6HSU at full load condition with 10%EGR. Thus it can be concluded that MPFI reduced smoke levels at full load conditions with higher EGR flow rates compared to SI combustion mode. Similarly for low and moderate fuel Injection pressure ranging between 200 bar and 300 bar SI combustion released less amount of smoke for all EGR flow rates as compared to MPFI. Thus the results conclude that smoke levels can be effectively reduced with SI combustion mode for all EGR flow rates for low and medium operating pressures while higher EGR flow rates at high pressure fuel injection is suitable for MPFI combustion mode.

5.7. NO_X emissions

Fig. 7 shows the variation of NO_x at different Injection pressure with EGR for different engine operating load conditions. NO_x formation reduces with increase in EGR flow rates. NO_x emissions reduced from 1339 ppm to 132 ppm under controlled EGR and Injection pressure. This is due to the decrease in rate of heat release rate, incylinder combustion temperatures and low peak pressures as seen in above graphs. NO_x increases with increase in engine load for both SI and MPFI strategies. This is due to the increase in fuel quantity as much of the fuel is burnt in the premixed combusiton resulting higher peak and combustion temperatures favoring NO_x formation Wei et al. [34]. Increase in EGR rates decreases the NO_x emissions for SI and MPFI combustion modes. Injection pressure is an influence parameter in controlling NO_x in addition to fuel injection strategies like retarded and split injections such as SI and MPFI modes. It is observed that with 0% EGR when the engine is running at design injection pressure of 200 bar MPFI system released 400 ppm while retarded injection at − 11° TDC i.e., SI case noted 1000 ppm. There is 150% decrease in NO_x is observed for MPFI compared to SI combustion mode. NO_x emissions drastically reduced from 986 ppm to 344 ppm at full load conditons at 350 bar injection pressure when EGR flow rate is increased from 0% to 10%EGR as seen in Fig. 7. When cooled EGR is circulated further reduction in $NO_x$is observed from 406 ppm to 282 ppm for MPFI mode. Hence it can be concluded that MPFI is effective in reducing the NO_x emissions for engines operating at the designed injection pressure. It is interesting to observe that when the fuel injection pressure is further increased to moderate higher values there is a shift in release of NO_x pattern. It can be seen that for injection pressure of 300 bar which is 50% higher than the design pressure SI combustion released 829 ppm while MPFImode released 962 ppm at full load operating conditions. Thus NO_x has increased by 12% for MPFI compared to SI case. On further increase in fuel injection pressure to 350 bar the results shows that MPFI with higher percentage of EGR i.e., 10%EGR is effective in reducing the emissions at all loads compared to 10%EGR with SI combustion. NO_x reduced to less than 200 ppm at full load conditions with 10%EGR rate for MPFI mode. Hence it can be concluded that there is a injection pressure map in which at design pressure and high operating pressure of 350 bar MPFI system under CRDI mode is very effective in reducing the NO_x emissions with 10% EGR flow rates. Where as at moderate high pressure injections up to 50% higher than the design injection pressure SI mode with 10% EGR rates is effective in reducing the NO_x emissions.

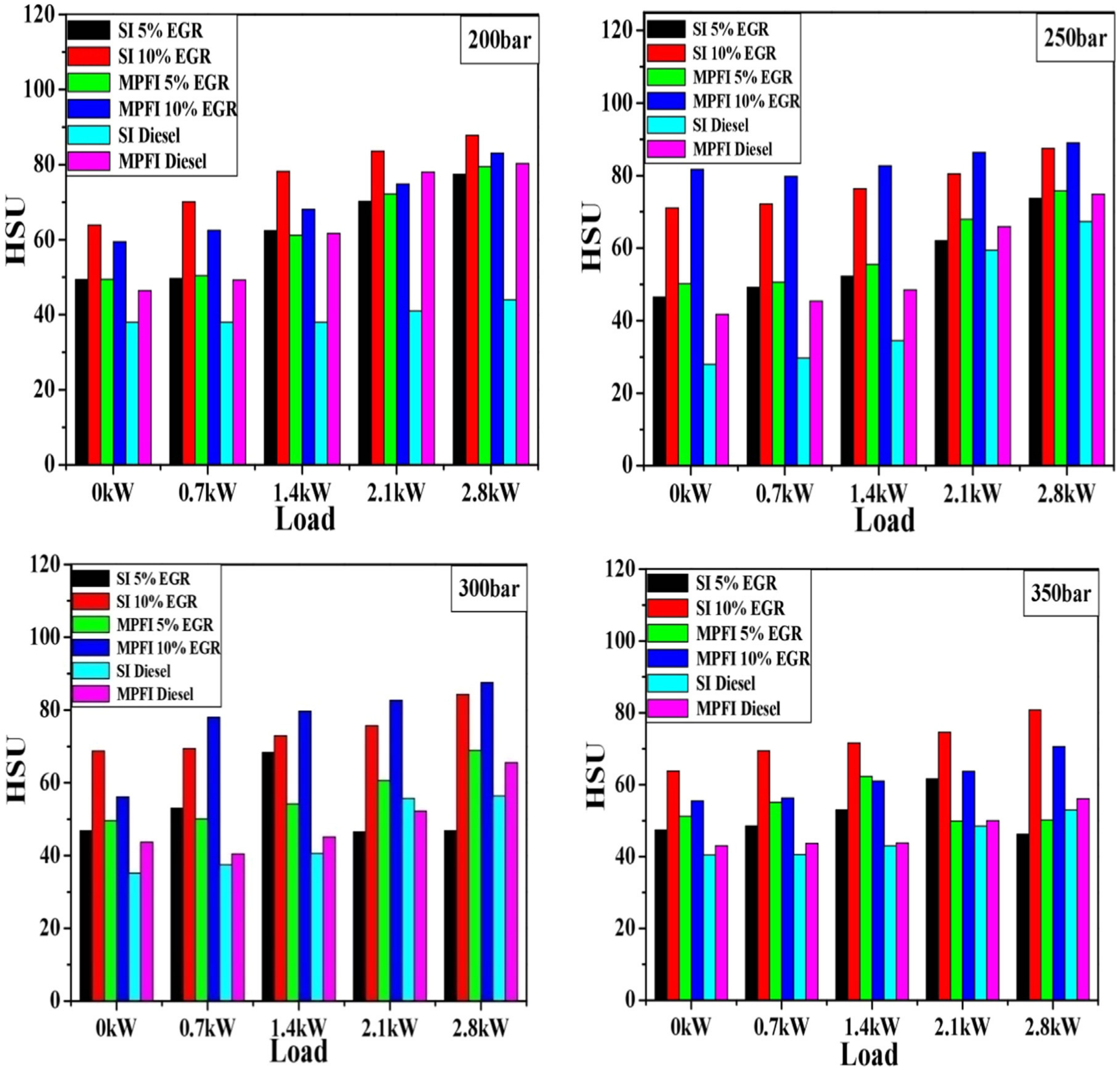

Fig. 6. Smoke emissions in HSU of SI and MPFI diesel combustion at varying injection presssures for at different EGR conditions.

6. Conclusions

The conventional direct injection single cylinder diesel engine is modified to run on high pressure fuel injection system in which fuel is injected by two strategies retarded injection (SI) and split injections (MPFI). The ultra-cooled EGR is circulated with different flow rates with high pressure fuel injected by modified CRDI system with electronic timing injection kit. The results show that MPFI system is most suitable for engine running on design pressure and high Injection pressure of 350 bar. Simultaneously for moderate and medium high pressures of 50% higher than the design pressures retarded injection SI system is having better performance than MPFI system. The following conclusions are obtained:

Higher EGR flow rates decreased the brake thermal efficiency marginally for both single retarded and split injections. Without EGR split injection has higher brake thermal efficiency than single retarded injection for all Injection pressure. Operating at full load condition for 10%EGR flow rates both retarded and split injections are exhibiting equal brake thermal efficiency of 30.11% at 350 bar injection pressure. At the same time split injection with 5%EGR flow rate the maximum thermal efficiency is 29.06% while SI system exhibits 33.61% brake thermal efficiency at 350 bar injection pressure. This shows that MPFI system exhibits marginal decrease in brake thermal efficiency compared to SI injection. Combustion analysis show that higher EGR flow rates was able to reduce the combustion peak pressures by 5.8%. Hence It can be concluded that Multiple injection strategy with high EGR flow rates is effective in reducing the combustion peak pressure for all Injection pressure compared to SI injections. For MPFI 10% occurance of Peak pressure is advanced from 48.13° to 51.87° while for 10%SI injection it is from 45.74° to 49.39°ATDC when the Injection pressure increases from 200 bar to 350 bar at full load conditions. It can be seen that higher peak pressures in the premixed combustion is

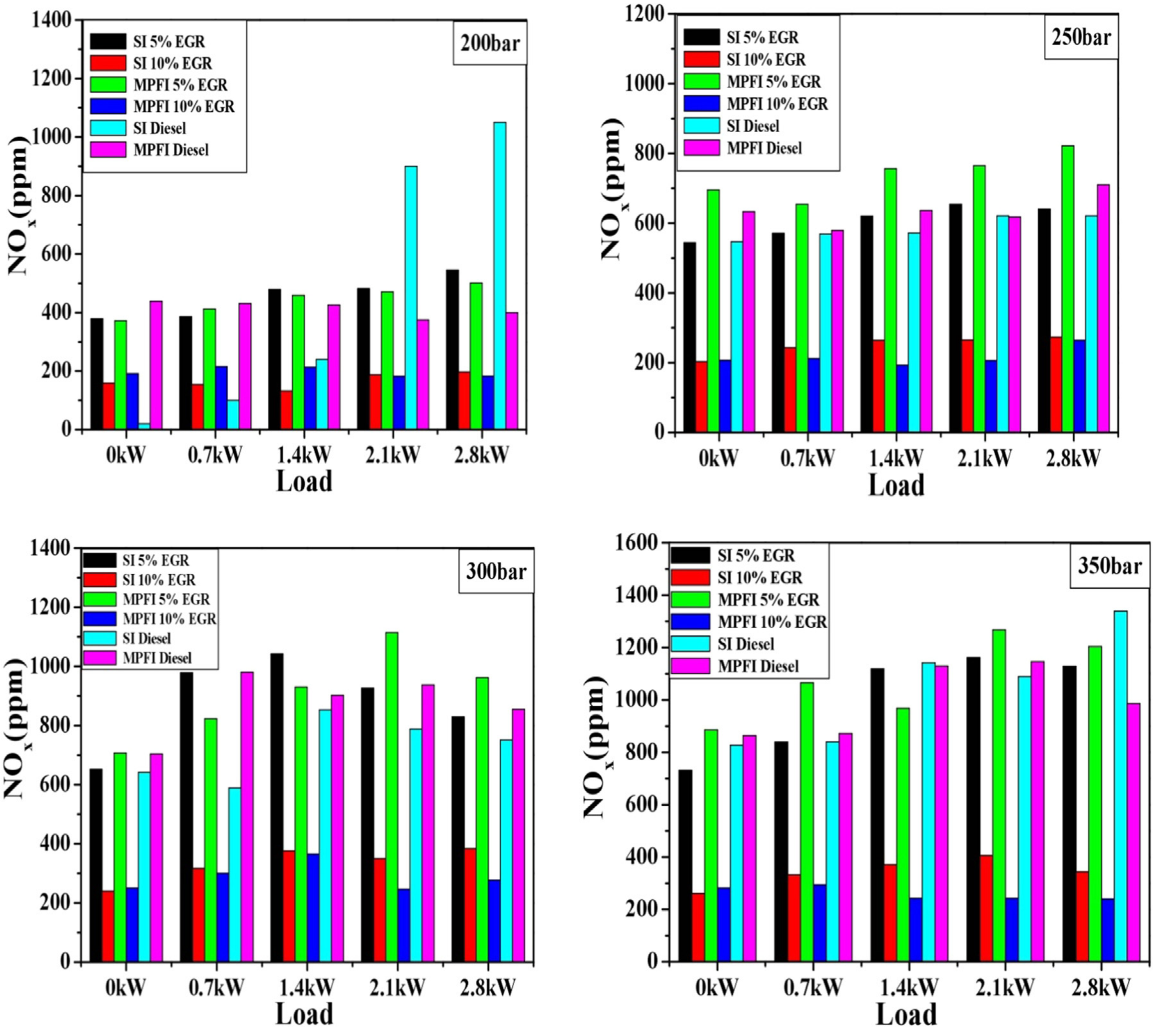

Fig. 7. NO_xemissions emissions of SI and MPFI diesel combustion at varying injection presssures for at different EGR conditions.

observed for 10%EGR where as 5% EGR flow rates has better premixed and improved controlled combustion. Thus it can be concluded that SI combustion for higher pressure combustion is suitable for low EGR flow rates. It was observed that EGR has positive effect on multiple injections for increase in Injection pressure as one can see that the ignition delay decreased with EGR circulation. 10% MPFI has lowest ignition delay of 2.4° compared to 5.15° for 5%SI at 300 bar injection pressure and full load engine operating conditions. MPFI heat release rate curves has 4 peaks showing the small peaks at − 38° and − 11° fuel injections while the remaining two high secondary peaks shows the low temperature and high temperature zones. Regarding HRR, MPFI fuel injection reduced the peak value of HRR compared to single retarded injection showing that MPFI technique at high pressure injection is an effective tool in reducing the peak value of HRR. 10% EGR has different HRR compared to 5%EGR for both retarted and multiple injections. Trade-off results are noticed for HRR value with 5%EGR and without EGR for both multiple and split injections. Peak value of HRR is decreased from 19.38 J/deg at 300 bar is reduced to 18.61 J/deg at 350 bar. Similarly HRR value is decreased from 20.07 J/deg at 300 bar to 19.50Jdeg at 350 bar for 5%SI retarded injection. Similar results are also observed for all EGR flow rates for both SI and MPFI strategies. Thus High pressure MPFI technique is an effective tool to control the combustion rate and improves the combustion process and safety of the engine structure when operated at high pressure fuel injection. There is 7.8% decrease in incylinder gas temperture when the EGR flow rate is increased by 5% for both SI and MPFI systems. In terms of smoke SI combustion releases smoke of 80.8HSU where as MPFI released only 70.6HSU at full load condition with 10%EGR. Thus it can be concluded that MPFI reduced smoke levels at full load conditions with higher EGR flow rates compared to SI combustion mode. NO_x emissions reduced from 1339 ppm to 132 ppm under controlled EGR and Injection pressure. NO_x emissions drastically reduced from 986 ppm to 344 ppm at full load conditons at 350 bar injection pressure when EGR flow rate is increased from 0% to 10%EGR. Higher percentage of EGR i.e., 10%EGR with MPFI system is effective in reducing the emissions at all loads compared to 10%EGR with SI combustion. NO_x reduced to less than 200 ppm at full load conditions with 10%EGR rate for MPFI mode The present research work shows that there is an injection pressure map in which at design pressure and high operating pressure of 350 bar MPFI system under CRDI mode is very effective in reducing the NO_x emissions with 10% EGR flow rates. Whereas at moderate high pressure injections up to 50% higher than the design injection pressure SI mode with 10% EGR rates is effective in reducing the NO_x emissions.

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Appendix A

	Coefficients	Standard error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	−0.011928	0.0416705	−0.28625	0.80161	−0.19122	0.167366	−0.1912	0.167366
torque (Nm)	−0.0106084	0.0028795	−3.68398	0.06642	−0.02299	0.001781	−0.023	0.001781
SFC	1.411064	0.1400022	10.07887	0.00970	0.808683	2.013446	0.80868	2.013446

Regression statistics	
Multiple R	0.991308436
R Square	0.982692416
Adjusted R Square	0.965384831
Standard Error	0.042519502

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