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Emission Reduction Strategies for Small Single Cylinder Diesel Engine Using Valve Timing and Swirl Ratio

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ABSTRACT

Small diesel engines are widely used for commercial vehicle and passenger car applications due to their higher torque requirements, fuel economy, and better thermal efficiency. These engines are exposed to different operating and environmental conditions and hence emissions from these engines are erratic. Strategies are required to enhance performance and reduce engine-out emissions considering environmental pollution and regulations. The main objective of this experimental study is to develop strategies for performance improvement and emission reduction for naturally aspirated engines, which can further be used for emission reduction of the multicylinder engine. Experimental work has been carried out on a single-cylinder naturally aspirated diesel engine to study the impact of engine operating parameters like valve timing, swirl ratio, and injection pressure on engine performance and emissions. Parameters considered for the study are: three intake valve opening timings, two fuel injection pump pressures, two-cylinder head swirls, and three start of injection timings. Results showed improvement in performance, lower exhaust gas temperature, and reduction of engine-out emission. Exhaust gas temperature was reduced by 5-18% with advanced valve opening and lower cylinder head swirl option. NO_x emission was reduced by 5-50% at advanced intake valve opening (IVO) options with retarded start of injection (SOI) and lower swirl cylinder head. This has a penalty on CO and HC emissions since the availability of fresh air is less due to higher internal exhaust gas recirculation (EGR). Higher pressure fuel injection pump helps in improving engine torque with an adverse effect on engine-out NO_x emission. As these engines are of low power capacity segment and are used in few countries, research on these engines is limited. All research work has been carried out in the field of intake valve closing timings, swirl ratio and injection timings; however, very limited research is available for the effect of intake valve opening timings due to practical limitations of the lower valve to piston clearance in diesel engines.

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NOMENCLATURE

CO	Carbon Monoxide	IVO	Intake Valve Opening
HC	Hydrocarbon	IVC	Intake Valve Closing
NO_x	Oxides of Nitrogen	LIVC	Late Intake Valve Closing
DI	Direct Injection	EVO	Exhaust Valve Opening
Abbreviations		EIVC	Early Intake Valve Closing
CRDI	Common Rail Diesel Injection	VVT	Variable Valve Timing
EGR	Exhaust Gas Recirculation	BSFC	Brake Specific Fuel Consumption
VVA	Variable Valve Actuation	CA	Crank Angle
TDC	Top Dead Center	SOI	Start of Injection

1. INTRODUCTION

Small diesel engines are widely used for commercial vehicle and passengers car applications in Asia. Its fuel economy along with minimum operational and maintenance cost make it more popular for urban and

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rural markets. These small engines are used in 3 wheelers, 4 wheelers and modified/make to order vehicles for different applications. Vehicles fitted with these engines are used in rough and narrow roads and extreme physical and environmental conditions. Being unmonitored, these vehicles emit higher emission than expected under various driving conditions. These emissions include CO, HC, and NO_x emissions which are among the major sources of environmental pollution. Stringent emission norms are brought by the government to curb these pollutions and make the environment cleaner and greener. All vehicle and engine manufacturers are working to meet these norms by upgrading engine and combustion using the latest technologies available in the market. This includes after-treatment devices, variable valve timing, twin-turbocharging, supercharging, low-temperature combustion, higher and cooler EGR, modern fuel injection pump, and nozzles. Research is also ongoing all around the world with these technologies individually or in combination for emission reduction. The present work is to study the effect of intake valve opening timing, injection pressure, start of injection (SOI), and swirl ratio on performance and emission reduction for small single cylinder naturally aspirated diesel engine.

Diesel engine development is mainly driven by stringent emission standards imposed by the government [1]. Emission legislation and control, new fuels, improved combustion and advanced concepts for energy saving are the major areas of combustion development [2, 3]. Oil-based fuel availability is also a problem due to limited reserves and political influences, which leads to significantly increased fuel costs [4]. Future diesel engine development is of importance to cope with increasing demands concerning emissions, energy consumption and due to the forecasted increase in road transport within India. The NO_x formation in diesel engines is mainly attributed to engine thermal management which increase exponentially with the temperature [5, 6]. The transport sector is one of the major contributors to global warming and environmental pollution [7].

Variable valve timing and variable injection timings with in-cylinder combustion are possible ways to meet upcoming restrictive emissions' requirements like NO_x and soot for DI diesel engines [8]. Zhang et al. [9] have studied the effect of late intake valve closing and rebreathing strategies on diesel engine performance and emission at low load, high-pressure CRDI system with Ex-EGR, and electro-hydraulic VVA system. Increasing valve lift and valve duration in 2IVO strategy were used to minimize CO and HC emissions. Fuel injection timings were kept closed to TDC with external EGR to control NO_x emissions with 3 IVC strategy. They concluded that a low level of NO_x was emitted with heavy EGR however, LIVC strategy was beneficial for smoke reduction. 2EVO strategy resulted in the lowest CO and HC emission with a penalty in smoke emission, while 2IVO maintained all emission at a low level with a slight penalty in fuel economy.

Zammit et al. [10] experimentally investigated the effect of EIVC and cylinder deactivation on 4 cylinder, turbocharged CRDI diesel engine on fuel economy and emission. At 2 bar BMEP and fixed NO_x level, soot emissions reduced with an increase in CO and HC emission. However, as the load increased the benefit of soot emission diminishes and the fuel economy penalty was negligible. They also observed that the compression ratio decreased from 15.2:1 to 13.7:1 during the earliest timing and VVA. EIVC increased ignition delay and 30% soot reduction was achieved while the increased level of CO and HC was lowered by lean mixture through injection pressure reduction. Experimental investigation of diesel engine for reducing NO_x emission by comparing standard dual cycle and Miller cycle was carried out by Wang et al. [11]. The Miller cycle was used to reduce the in-cylinder temperature at the end of compression and to achieve lower temperatures at the end of combustion which resulted in the reduction of NO_x emission. Results showed that NO_x emission was reduced by 4.4% to 17.5% for varying load when three versions of the Miller cycle were applied to a diesel engine in which Miller cycle 1 gave the best reduction by 11.0% to 17.5%.

Tomoda et al. [12] studied the effect of VVT and variable valve lift to improve the thermal efficiency of the diesel engine and maintain low emission level. The benefits of the valve overlap approach were reduced pumping losses, enhancement of volumetric efficiency, and control of residual EGR fraction. To vary swirl ratio continuously, IVC timing of VVT system was changed continuously. At high loads, the used VVT system could flexibly change the engine parameter, which resulted in 40% reduction in NO_x emission and 4% improvement in fuel economy. Low-end torque increased by 40% by matching EVO and overlap of IVO and EVO around TDC which resulted in the utilization of exhaust pressure pulsation. Experimental investigation on modification of in-cylinder gas thermodynamic condition by advancing the IVC angle in a HD diesel engine was studied by Benjas et al. [13]. They observed, advancing IVC reduced the total mass flow rate and decreased the effective compression ratio. Both pressure and density were reduced by 21.5% whereas temperature was decreased by only 2.3% at TDC as compared with the nominal IVC profile. Advancing IVC resulted in an increase of soot and CO emission, extremely low HC emission with the reduction in thermal and engine efficiency. To obtain low NO_x level, intake oxygen mass concentration was maintained at 17.4%.

Deng and Stobart [14] carried out BSFC investigation using VVT on a HD diesel engine and observed that engine performance and fuel efficiency were significantly influenced by IVC due to its huge effect on volumetric efficiency. About 2.3% BSFC benefit was produced in either EIVC or LIVC as it has reduced pumping losses at part load and 1600 rpm; however, at 2200 rpm and full load condition 6% BSFC benefit was achieved by LIVC. Retarded exhaust valve phasing produced 1% BSFC benefit however, BSFC increased with delayed EVO. Therefore, as a result of investigation maximum 6% BSFC benefit could be achieved in different VVT strategies. Ghajar et al. [15] proposed a semi-empirical model, with engine speed, load, and valve timing for the prediction of volumetric efficiency. The developed model, its accuracy, and generalizability correlated with experimental data over an extensive working range of three distinct engines. Normalized test errors achieved were 0.0316, 0.0152, and 0.24 for three engines, respectively.

VVA is a standard technology to maximize volumetric efficiency over a wide range of engine speeds and loads [16]. Kim et al. [17] examined the effect of LIVC strategies in a single-cylinder compression ignition engine. IVC timings of 28˚CA, 44˚CA, 68˚CA, and 88˚CA with multiple injection strategies were studied for NO_x emission reduction. They observed that the volumetric efficiency decreased owing to the backflow of the cylinder charge into the manifold which implied that intake boosting was necessary. It was observed that the decrease in effective compression ratio from 16:1 to 13.7:1 at IVC timing 88˚CA resulted in 24.1% reduction of NO_x concentration, whereas reduction in O_2 concentration from 21% to 15% resulted in 78% reduction of NO_x concentration. Prolonged ignition delay, which provided a longer time for mixture formation, resulted in a reduction in the smoke emission.

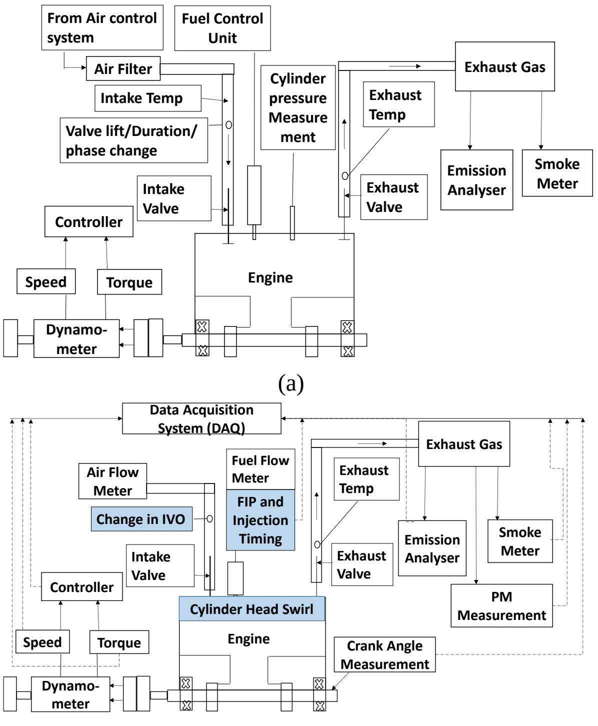
Previous studies showed the effect of IVC, EVO, and EVC valve strategy on performance and emissions reduction. The majority of the works involved CRDI system or Ex-EGR or EIVC or LIVC strategy or a combination of these at varying load conditions for NO_x, CO, and HC emission reduction. IVO timing remained unchanged in most of the studies due to the practical limitation of the valve-piston clearance at TDC for diesel engines. Therefore, it is necessary to develop effective strategies to achieve low NO_x, CO, and HC emissions while maintaining performance. The main objective of this experimental work is to study the effect of valve timing, injection pressure, SOI, and swirl on small diesel engines for performance improvement and emission reduction. This study also explores intake valve timing strategies for internal EGR to reduce engine-out NO_x emission for naturally aspirated diesel engines.

2. EXPERIMENTAL TEST SETUP

Experimental work has been carried out on air-cooled four-stroke single-cylinder direct injection diesel engine with a displacement volume of 0.43 liter and compression ratio of 19:1. The power output produced by the engine was 5.5 kW at 3600 rpm. Detailed specifications of the engine are given in Table 1. The test setup is shown in Figure 1a and b, wherein in-cylinder pressure is measured by a piezoelectric pressure transducer (Kistler make). The pressure transducer is flush-mounted in cylinder head bottom surface for accurate measurement and to avoid hindrance due to fuel spray. Fuel is supplied from an overhead tank to the fuel conditioning unit and from there it is supplied at the pressurized condition with the return line carrying the bypass. The turbine flow meter is used for the measurement of the intake air flow rate. AVL make encoder (consisting of an optical disc) is mounted on the engine dynamometer side for engine rpm measurement. The engine is instrumented to measure the inlet and exhaust gas temperature and Chromel-alumel (K-type) thermocouple is mounted at a distance of 50-100 mm for accurate measurement. Cylinder pressure, top dead center (TDC), crank position, and all other signals are acquired by a high speed digital multifunctional I/O module, A-D converters, signal conditioner for data acquisition and control (AVL Puma Graz, Austria). AVL AMA emission analyzer is used for the emission measurement, where it takes a certain amount of sample from the exhaust emission at temperatures higher than 200˚C. Separate lines are used for the measurement of NO_x, and HC emission. Flame ionization detector (FID) is utilized for determining the unburned hydrocarbon emission level from the combustion chamber. Nitric oxide emission in the exhaust is measured with a chemiluminescence analyzer. Various sensors and uncertainty are shown in Table 2.

TABLE 1. Brief engine specifications

Type	**Four strokes, air-cooled, single-cylinder, CI engine**
Fuel	Diesel
Number of cylinders	One
Bore/Stroke	1.146
Compression ratio	19±0.5
Rated power	5.5 kW @ 3600 rpm
Rated torque	18 Nm @ 2000-2400
Valve timing	Inlet valve opening (IVO) : 7° before TDC Inlet valve closing (IVC) : 45° after BDC Exhaust valve opening (EVO):35° before BDC Exhaust valve closing (EVC) :28° after TDC Valve last 0.6-0.7 mm Max lift for intake and exhaust: 7.6 mm



(a)

(b)

Figure 1. (a) Schematic view of the experimental set up; (b) Engine mounting view on test bed

3. TEST MATRIX

Initially, baseline engine performance and emission are measured, and thereafter effect of FIP in terms of injection pressure, valve timing, swirl ratio, and SOI are analyzed. The effect of each parameter is analyzed individually and in combination and few cases of performance and emission improvement are discussed. Three IVO timing, two swirl ratios, two FIP injection pressure, and three SOI are analyzed; the test cluster and test matrix are mentioned in Table 3. All engine specifications and other parameters remain the same for all the cases except the parameters mentioned in Table 3. Total 12 cases will be discussed, wherein the effect of individual parameters and combination is analyzed and discussed for different IVO, FIP SOI, and swirl ratios.

4. RESULT AND DISCUSSIONS

Initially, baseline engine testing is carried out and results are analyzed. Baseline engine performance and emission results are shown in Figure 2a and b. Peak engine torque measured was 19.5 Nm@2000 rpm with engine out exhaust gas temperature of 672˚C. NO_x and CO emission curves are shown in Figure 2.

The effect of various engine operating parameters is discussed in further sections.

4. 1. Effect of Fuel Injection Pump (FIP)

An increase in fuel injection pump pressure increases the injector end pressure. The injector injects fuel at a higher pressure into the combustion chamber. This higher pressure gives better atomization and hence helps in better fuel-air mixing. This increases the quality of combustion and affects performance and emissions. Increased injection pressure fuel pump on baseline engine configuration increases NO_x emission by 15% for max torque speed, however, rated speed NO_x remains unchanged as shown in Figure 3a. Exhaust temperature (Figure 3b) also follows the same trends with lower values at rated speed with akin values at other engine

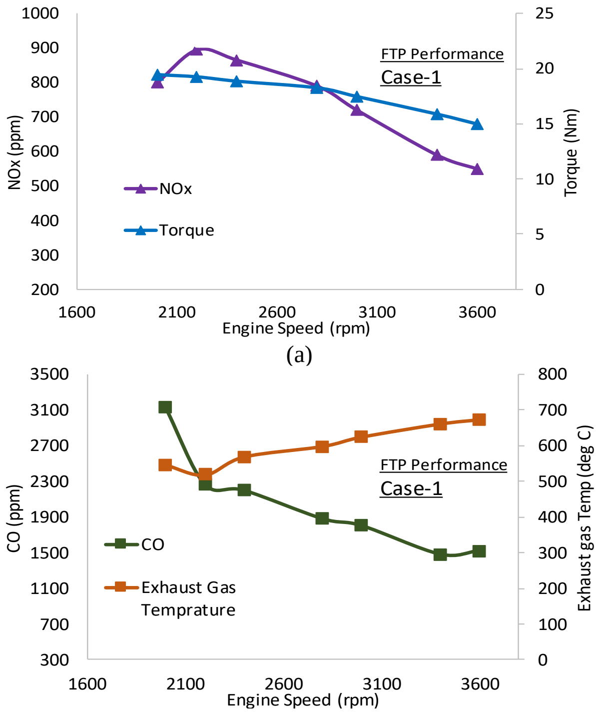
TABLE 2. Various measuring instruments and its uncertainty

Sr.No.	Measuring instruments	Make	Accuracy	Uncertainty (%)
1	Airflow meter	ABB SENSYFLOW-SFI-05	± 0.5% full scale reading	± 0.9
2	Fuel flow meter	Emerson, India-FI-05	± 0.5% of full-scale reading	± 0.9
3	Pressure pick up Piezo-electric	KISTLER, Switzerland-HSDA-01	± 0.4% full-scale reading	±0.85
4	Pressure pick up Piezo-resistive	KISTLER, Switzerland-HSDA-02	± 0.4% full-scale reading	±1.05
5	Emission analyzer	AVL Emission Test Systems, Germany-AVL AMA i60-03	CO: ± 0.07% of full-scale reading CO_2: ± 0.53% of full-scale reading NO_x : 0.53% of the full-scale reading THC : 0.53% of full-scale reading	± 3.92
6	Torque speed	Benz Systems, India	± 0.25% of full-scale reading ± 0.54% of full-scale reading	± 2 ± 0.5
7	PM measurement	AVL Emission Test Systems, Germany-AVL 472-04(A)	±0.53% of full-scale reading	± 3.9
8	Smoke	AVL Opcimeter439-05	± 0.25% of full-scale reading	± 0.9
9	Charge amplifier	KISTLER, Switzerland	± 1% full-scale reading	
10	Crank angle encoder	AVL, Austria	0.1 °CA	
11	Digital data acquisition system	AVL Puma Graz, Austria	± 2 bit	
12	Thermocouple (K-type)	HI-TECH Transducers & Devices, India	± 0.75% of full-scale reading	± 2

TABLE 3. Test cluster and matric

Parameters	**Considered values**
IVO timing	a) 15° bTDC b) 30° bTDC c) 45° bTDC
FIP pressure (bar)	a) Baseline FIP-1: 327 and b) FIP-2 - 364 bar
Swirl ratio	a) Head-1 swirl 2.5 and b)Head -2 swirl 2.0
SOI	11°, 9°and 7° bTDC

Case No	**Parameters description**
Case-1	Baseline engine configuration
Case-2	FIP-1, IVO-15˚, Head-1, SOI-11˚ bTDC
Case-3	FIP-2, IVO-30˚, Head-1, SOI-11˚ bTDC
Case-4	FIP-2, IVO-45˚, Head-1, SOI-9˚ bTDC
Case-5	FIP-1, IVO-45˚, Head-2, SOI-11˚ bTDC
Case-6	FIP-2, IVO-30˚, Head-2, SOI-9˚ bTDC
Case-7	FIP-2, IVO-45˚, Head-1, SOI-7˚ bTDC
Case-8	FIP-1, IVO-45˚, Head-1, SOI-9˚ bTDC
Case-9	FIP-1, IVO-45˚, Head-2, SOI-9˚ bTDC
Case-10	FIP-1, IVO-45˚, Head-2, SOI-7˚ bTDC
Case-11	FIP-2, IVO-45˚, Head-1, SOI-9˚ bTDC
Case-12	FIP-2, IVO-45˚, Head-2, SOI-7˚ bTDC



(a)

(b)

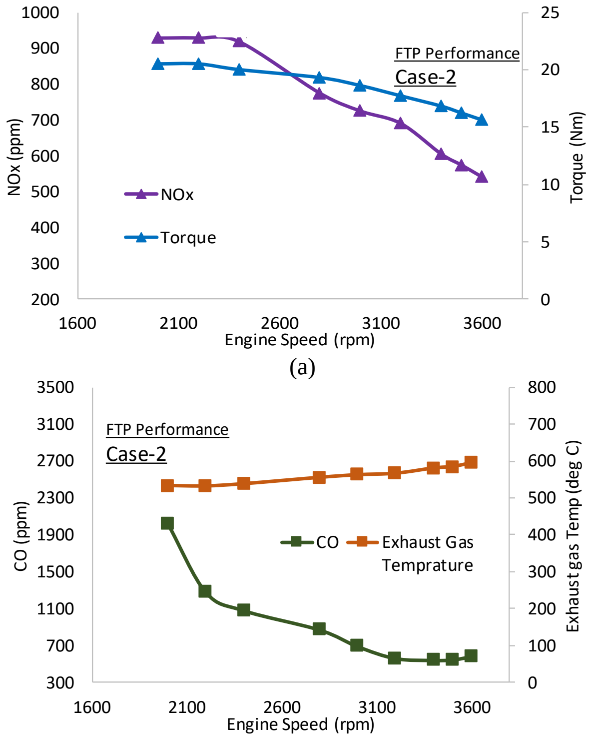
Figure 2. (a) NO_x emission and engine torque vs engine speed for baseline engine configuration; (b) CO emission and exhaust gas temperature vs engine speed for baseline engine configuration

speeds. As shown in Figure 3a, engine maximum torque is increased by 5% with a reduction in CO emission. It is due to higher in-cylinder pressure and consequently, the temperature which is a favorable condition for NO_x formation and this is the main reason for higher NO_x emission. As other engine parameters are the same, HC emission increases with reduction in CO emission. These results are in line with the results of Zammit et al. [10] and Kim et al. [17].

The effect of higher injection pressure with advanced IVO and retarded SOI is discussed in further sections.

4. 2. Effect of Early Intake Valve Opening

Advance IVO timing opens the intake valve earlier than TDC and provides higher valve overlap between intake and exhaust valve. This higher valve overlap allows us to send back a portion of high-temperature exhaust gases into the intake manifold. During suction, these high-temperature exhaust gases come back into the combustion chamber with fresh air. This mixing of exhaust gases with fresh air dilutes the intake air and increases incoming air temperature. Higher injection pressure also contributes to increased combustion chamber pressure and temperature. This initial higher temperature incoming air along with higher combustion temperature are favorable conditions for the formation of NO_x emission, however, diluted air reduces the oxygen



(a)

(b)

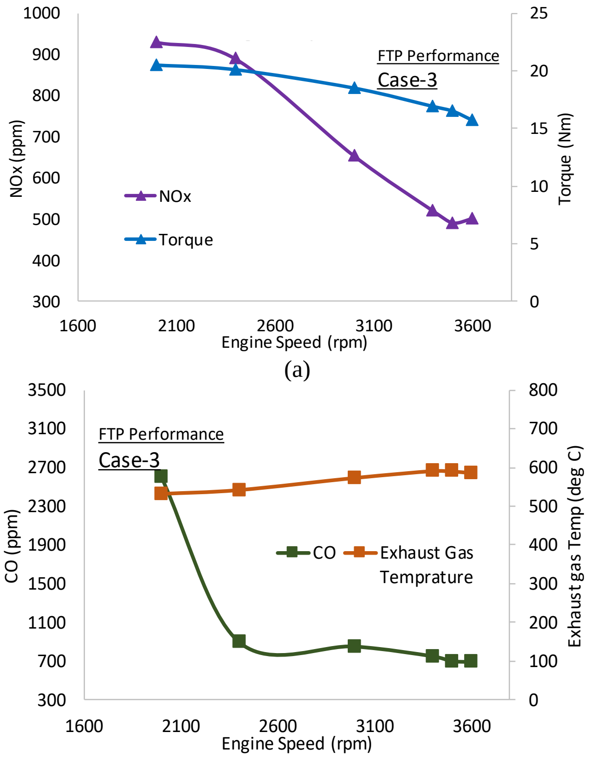
Figure 3. (a) NO_x emission and engine torque vs engine speed for FIP-2; (b) CO emission and exhaust gas temperature vs engine speed for FIP 2

availability and hence reduces NO_x emission [11]. The practical issue of adapting advanced IVO is intake valve to piston clearance which reduces as we advance IVO. Valve pocket needs to be provided on the piston to avoid this problem which increases the piston bowl volume and decreases the compression ratio. Baseline engine didn't have a pocket, however, the pocket of 1.6 and 2.5 mm depth is provided to maintain minimum valve to piston clearance of 1% of bore size for intake valve.

Advancing the IVO timing to 30˚bTDC leads to NO_x emission reduction by 10% for rated engine speed as shown in Figure 4a. This effect is uniform except at maximum torque speed where it is slightly higher than the baseline engine. Higher valve overlap duration minimizes the fresh air availability due to dilution with exhaust gases. This helps in the reduction of NO_x emission as limited oxygen is available for NO_x formation. Exhaust gas temperature trends also justify this, as it is decreased by 50°C (9%) for rated engine speed while was approximately the same for engine torque-speed. As shown in Figure 4b, CO emission also reduced in the range of 17-56% at various engine speeds compared to the baseline engine. HC emission from the engine also increased. It shows incomplete combustion due to lower oxygen availability. As combustion and exhaust gas temperatures are lower, they help in the reduction of CO formation. Higher engine speed favors higher valve overlap as it helps in feeding more air into the combustion chamber in shorter time, however, at low engine speeds, this higher valve overlap leads to higher backflow of air and thus reduces volumetric efficiency.

Advancing IVO to 45˚bTDC with retarded SOI, further reduces the NO_x emission for all engine speeds. In this case engine torque is increased by 2.5-5% at various engine speed ranges compared to the baseline engine, however, slightly lower than 30˚bTDC case. Exhaust gas temperature is also reduced by 3.6 to 11% at various engine speeds with minimum reduction at max torque speed. Advanced IVO increases valve overlap duration, which further minimizes the fresh air availability. This deteriorates the combustion quality, thus exhaust gas temperature is also reduced. CO emission is reduced due to lower peak combustion pressure and temperature, this increases HC emission due to incomplete combustion [13]. The effect of 45˚bTDC IVO on performance and emission is shown in Figure 5a and 5b.

Incomplete combustion and rich/lean fuel-air mixture are the reason for CO emission wherein, maximum combustion temperature is ≤1250˚C. Higher injection pressure with advanced injection timing also leads to higher penetration of fuel droplets and these fuel droplets



(a)

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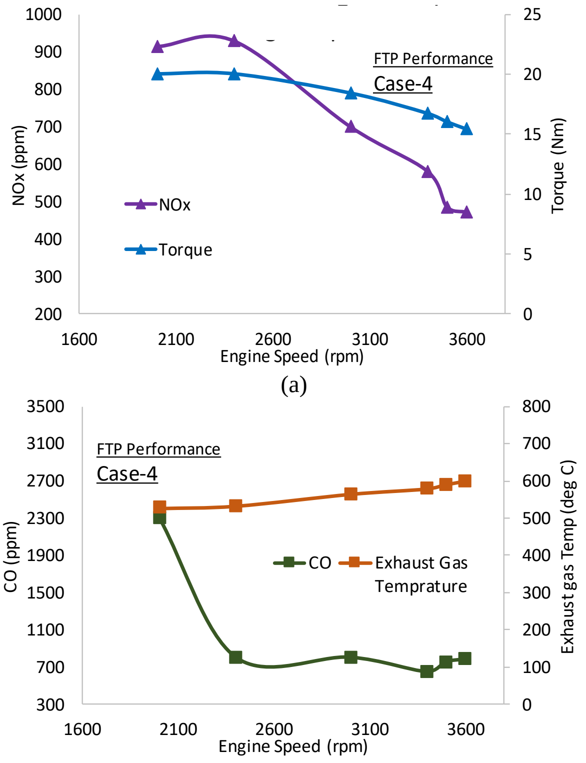
Figure 4. (a) NO_x emission and engine torque vs engine speed for 30˚bTDC IVO; (b) CO emission and exhaust gas temperature vs engine speed for 30˚bTDC IVO



(a)

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Figure 5. (a) NO_x emission and engine torque vs engine speed for 45˚bTDC IVO; (b) CO emission and exhaust gas temperature vs engine speed for 45˚bTDC IVO

lead to partial and incomplete combustion and contribute to higher CO and HC emission. As the reverse flow phenomenon is higher for lower engine speeds, it contributes more to max torque speed and consequently, the emission is higher at this speed.

4. 3. Effect of Swirl Ratio

Cylinder head swirl helps in mixing of air with injected fuel. This swirling motion of air helps in breaking fuel droplets and automization. The flow coefficient of the intake port shows the resistance of the port. It should allow maximum air with minimum resistance along with the desired swirl for better mixing. Swirl is the rotational momentum of air about the arbitrary axis parallel to the cylinder axis. Higher swirl helps in better mixing of fuel with air, however higher swirl leads to higher NO_x emission.

Cylinder head mounted on the baseline engine is tested for the swirl ratio and flow coefficient on the steady-state swirl test rig. It is found that the baseline cylinder head swirl is 2.59 with flow coefficient of 0.279. The flow coefficient of the baseline cylinder head is on the lower side and needs to be modified to reduce the port restrictions and to increase the flow coefficient. Cylinder head swirl is modified on steady-state swirl rig and this increases the flow coefficient on 2nd cylinder head. The baseline performance of 2nd cylinder was similar to the baseline cylinder head. The modified swirl ratio and flow coefficient for 2nd cylinder head are 1.91 and 0.310. These values are 26% lower for the swirl ratio and 11% higher for the flow coefficient compared to the baseline cylinder head. Performance comparison of the swirl ratio and flow coefficient is shown in Figure 6. The 2nd cylinder head is used on the engine with various IVO timings, SOI timing, and FIP pump to analyze the effect of the swirl ratio.

Lower swirl (Swirl -2) cylinder head with advanced IVO of 45˚ bTDC and baseline FIP configuration shows reduction of NO_x emission by 27%. CO emission in this case also reduces by 21.5% compared to the baseline engine. HC emission increases in this case. Peak engine torque is increased by 3% with 12.5% reduction in exhaust gas temperature. Figure 7 shows the effects of performance and emission for this case. Lower swirl increases mixture formation time and this delay in fuel-air mixing leads to incomplete combustion of fuel. This affects CO and HC emission. In-cylinder airflow pattern and squish inside the bowl are the other reasons for this higher HC emission.

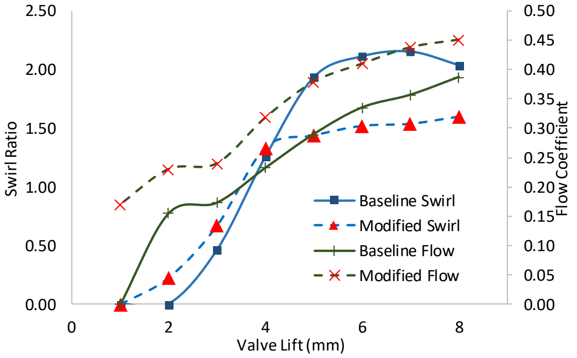
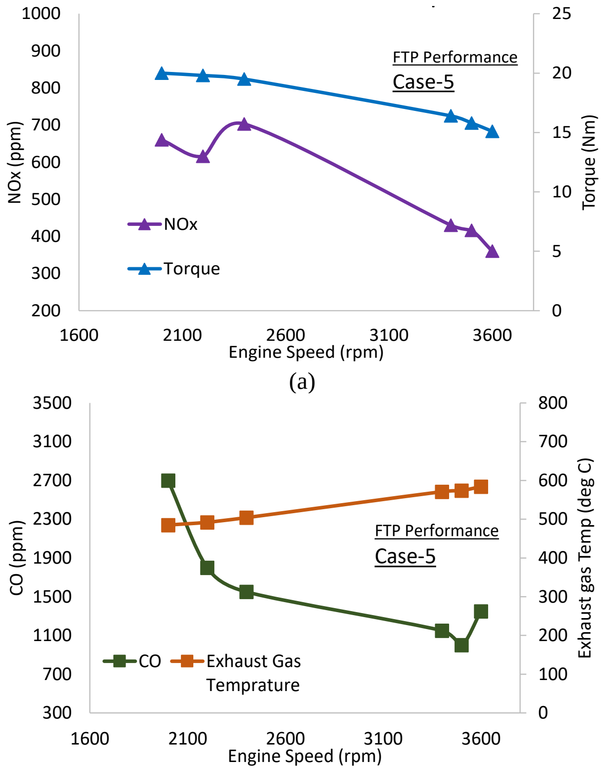


Figure 6. Swirl ratio and flow coefficient for baseline and modified cylinder head

4. 4. Effect of Start of Injection Timing

Injection timing influences fuel atomization, ignition delay, premixed combustion, and main combustion. Hence combustion rate is directly governed by SOI timing. Advancing and retarding SOI controls the combustion and hence performance and emission. SOI timing is modified by changing the shim thickness as the injection system is a unit injector pump with fuel cam.

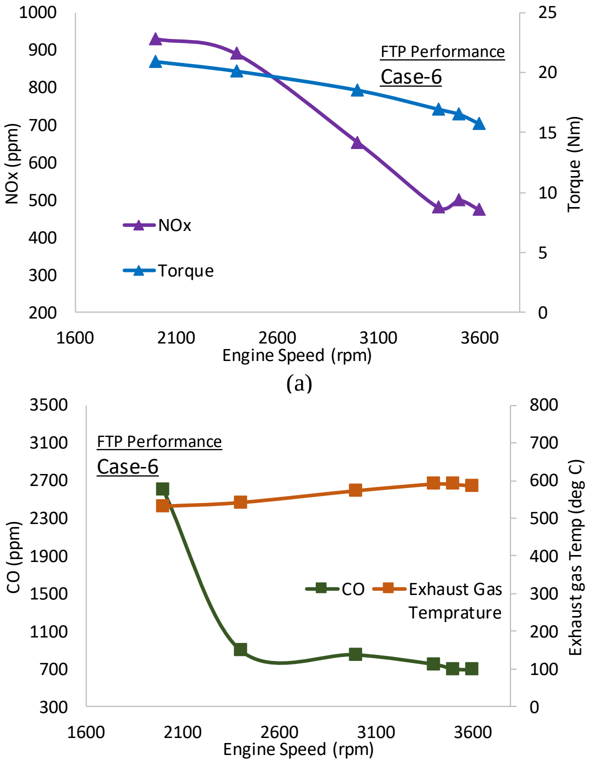
Retarded SOI of 9˚ with 30° bTDC IVO shows peak torque improvement of 7.2% (Figure 8a). This increases in HC emission by 200% with reduction of CO emission by 49% (Figure 8b). Retarded SOI and swirl-2 head increase fuel-air mixing time however, higher injection pressure and in-cylinder pressure affect combustion. Exhaust gas temperature is reduced by 6%. It is due to lower swirl and advanced IVO, which reduces oxygen



(a)

(b)

Figure 7. (a) NO_x emission and engine torque vs engine speed for swirl-2 cylinder head & 45˚bTDC IVO; (b) CO emission and exhaust gas temperature vs engine speed for swirl-2 cylinder head & 45˚bTDC IVO



(a)

(b)

Figure 8. (a) NO_x emission and engine torque vs engine speed for 9˚ SOI; (b) CO emission and exhaust gas temperature vs engine speed for 9˚ SOI

availability and momentum of air inside the combustion chamber. NO_x emission in reduced by 11% compared to the baseline engine.

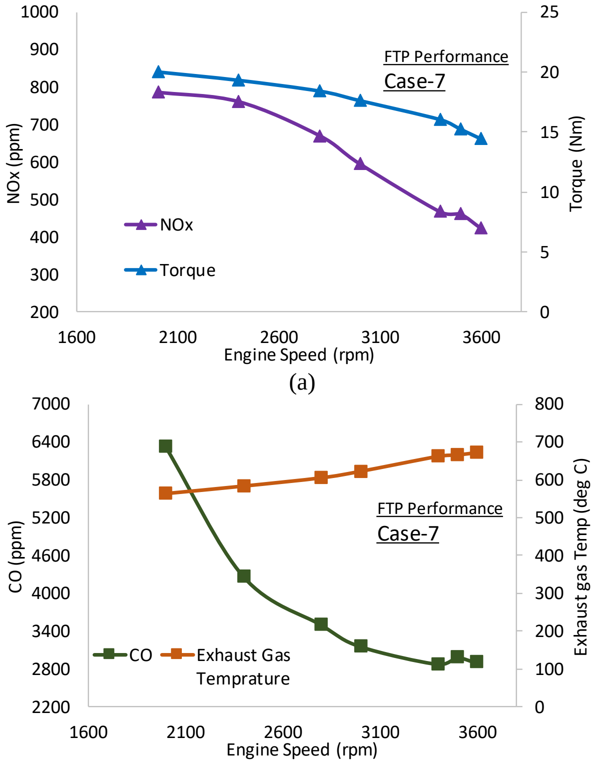
Retarded SOI of 7˚, with advanced IVO of 45° bTDC leads to reduction in NO_x emission by 15% with rated speed NO_x reduction by 22.9%, however, this effect is minimum at max torque engine speeds where this improvement is limited to only 2% as shown in Figure 9a. CO emission (Figure 9b) is increased by 100%, while HC emission is increased by 8%. Advanced intake valve opening leads to higher exhaust backflow and higher internal EGR, which increases the incoming air temperature. Retarded SOI delays injection and consequently fuel-air mixing, however higher in-cylinder pressure and temperature helps in rapid combustion. This increases the combustion rate with abruptly high pressure and temperature. Due to lower compression ratio, mixing quality, atomization, and oxygen availability favor for NO_x emission reduction [10, 16] as shown in Figure 9a. Due to abrupt combustion, exhaust gas temperature is higher (Figure 9b) and the same as per the baseline engine.

4. 5. Effect of Variation of SOI, FIP, IVO and Swirl

Injection timing influences the combustion rate, peak pressure, temperature, and emissions. FIP helps in better atomization of fuel and helps in the mixing of fuel with air. IVO helps in diluting the air and consequently the combustion and emission. Swirl ratio also plays a role in reduction of NO_x emission. The effect of variation in these parameters on performance and emission is discussed in this section.

SOI of 9˚ with advanced IVO of 45° bTDC, baseline FIP, and cylinder head reduces NO_x emission by 6%. Rated speed NO_x is reduced by 32%, however, max torque-speed NO_x is slightly higher. CO emission, in this case, is less than the baseline engine and lowest among all the cases discussed with a slight penalty in HC emission. It is due to better fuel-air mixing due to higher swirl and retarded SOI. Advanced IVO timing also maintains oxygen availability required for combustion, which restricts NO_x and CO formation. Exhaust gas temperature is reduced in the range of 8-15% at wide engine speeds. The effect of retarded SOI of 9˚ with advanced IVO of 45° bTDC is shown in Figure 10. This strategy is good for CO emission reduction.

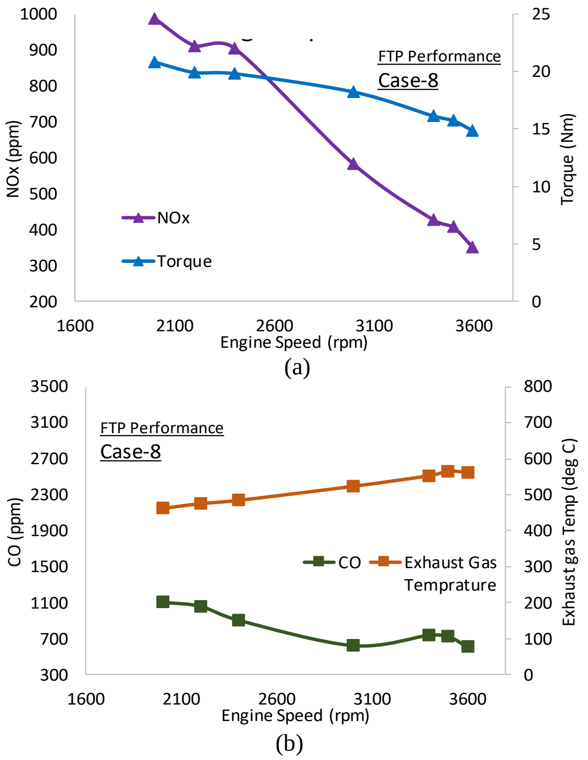
Retarded SOI of 9˚, IVO of 45˚bTDC, baseline FIP, and swirl-2 cylinder head strategy show the reduction in NO_x emission by 29% and reduction in exhaust temperature by 10% as shown in Figure 11a and b. CO emission increased in this case compared to the baseline engine. This points out to the availability of oxygen in a



(a)

(b)

Figure 9. (a) NO_x emission and engine torque vs engine speed for 7˚ SOI; (b) CO emission and exhaust gas temperature vs engine speed for 7˚ SOI



(a)

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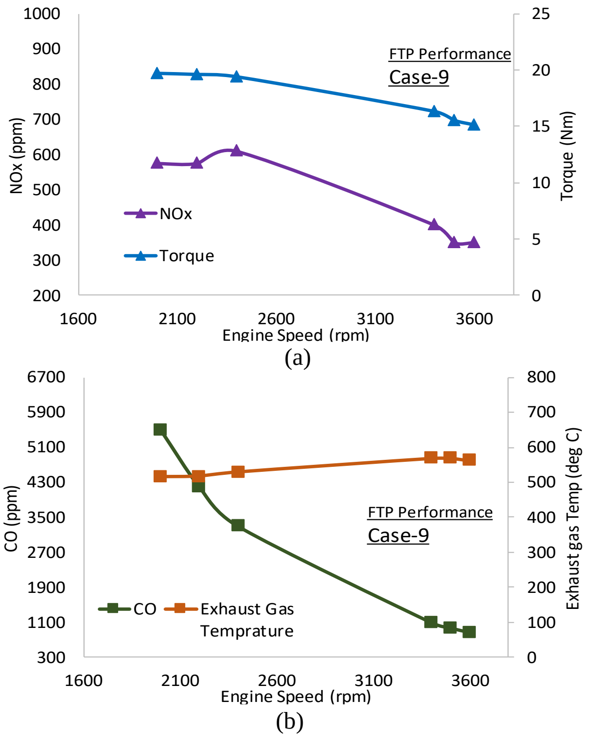
Figure 10. (a) NO$_x$ emission and engine torque vs engine speed for 9˚ SOI and 45° IVO; (b) CO emission and exhaust gas temperature vs engine speed for 9˚ SOI and 45° IVO

small naturally aspirated engine with very advanced IVO timing. The compression ratio and volumetric efficiency of the engine decrease with advanced IVO, higher valve overlap, and internal EGR effect [10]. The engine torque for this combination strategy remains the same as the baseline engine. Rated speed CO emission is reduced by 42%, however max torque CO emission is increased by 75%. Retarded SOI, lower injection pressure FIP, and swirl resulted in uneven air-fuel mixing and lower oxygen availability due to advanced IVO which are the reasons for uneven CO emission as shown in Figure 11b.

Swirl-2 cylinder head, SOI of 7˚, IVO of 45˚bTDC and FIP-2, reduce the NO$_x$ emission by 44%. This emission is reduced by 50% for rated engine speed while 30% for max torque-speed [12]. CO emission is reduced by 54% with an increase in HC emission. Lower swirl delays the mixture formation and leads to diverse mixing of the fuel-air mixture. The combustion rate is increased by delayed SOI and advanced IVO dilutes the air availability. Engine torque is reduced by 16-20% at various engine speeds with peak torque value of 16.3 Nm. This incomplete combustion also lowers the exhaust temperature by 30% compared to the baseline engine. This strategy has a penalty on the BSFC of the engine [14]. The effect of lower swirl with retarded SOI and advanced IVO on engine performance and emission is shown in Figure 12a and b.



(a)

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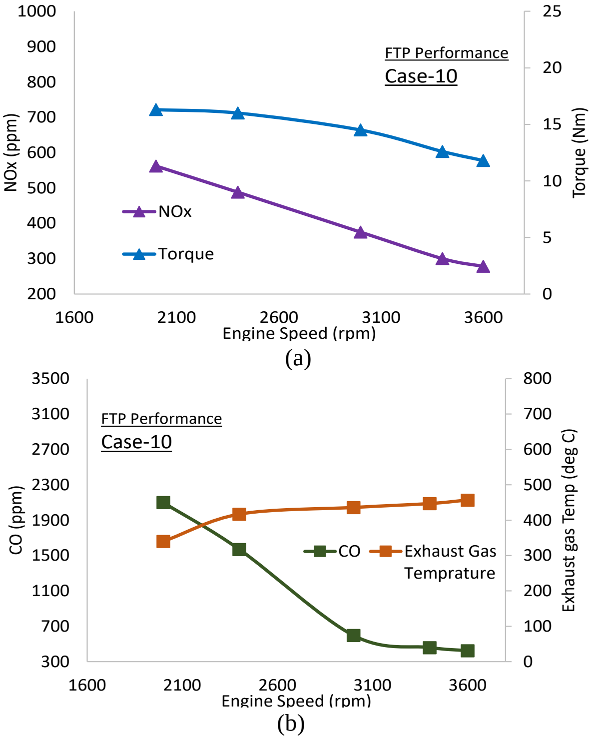
Figure 11. (a) NO$_x$ emission and engine torque vs engine speed for 9˚ SOI, 45˚ IVO and swirl-2 cylinder head; (b) CO emission and exhaust gas temperature vs engine speed for 9˚ SOI, 45˚ IVO and swirl-2 cylinder head



(a)

(b)

Figure 12. (a) NO$_x$ emission and engine torque vs engine speed for 7˚ SOI, 45˚ IVO and swirl-2 cylinder head, (b) CO emission and exhaust gas temperature vs engine speed for 7˚ SOI, 45˚ IVO and swirl-2 cylinder head

SOI of 9˚, IVO of 45˚bTDC, baseline cylinder head, and FIP-2 combination strategy increases the engine's peak torque by 9% with reduction in CO emissions by 8.5% as shown in Figure 13 and Figure 14. Rated speed CO emission is reduced by 61% while max torque-speed CO emission is increased by 86%. Engine out NO_x emission also decreased marginally by 4% compared to the baseline engine. HC emission increased slightly compared to the baseline engine. Higher incoming air temperature due to internal EGR, higher swirl, and higher FIP injection pressure increase the combustion temperature. Oxygen availability due to advanced IVO is the reason for uneven CO emission and higher HC emission.

SOI of 7˚, IVO of 45˚bTDC, swirl-2 cylinder head, and higher injection pressure FIP-2 strategy reduce NO_x emission by 42%. HC emission, in this case, is also increased compared to the baseline engine. CO emission, in this case, increases by 78% with marginal increases in peak torque. Exhaust gas temperature is close to baseline engine configuration. It is due to delayed SOI and rapid combustion, which increases the exhaust gas temperature. Over lean fuel-air mixture leads to an increase in HC emission. The effect is shown in Figure 15.

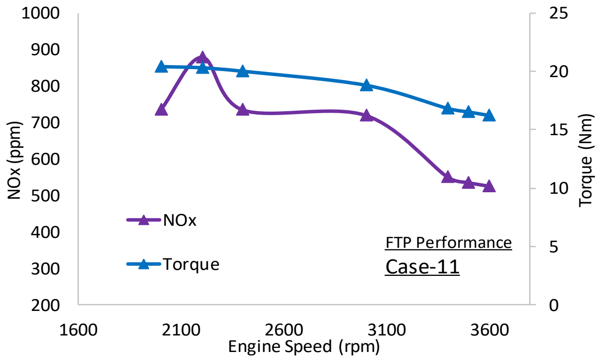


Figure 13. NOx emission and engine torque vs engine speed for 9˚ SOI, 45˚ IVO and FIP-2

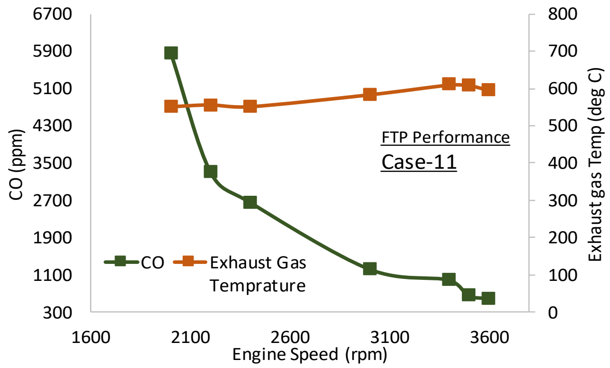
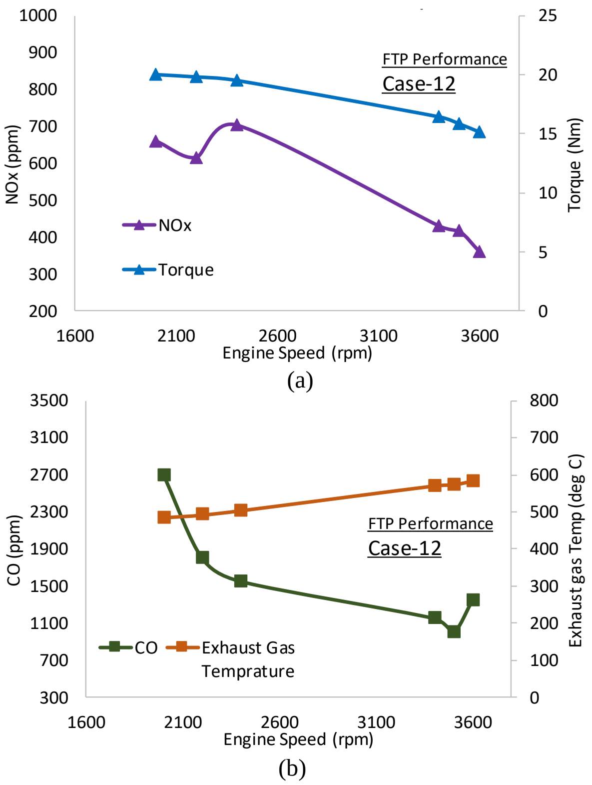


Figure 14. CO emission and exhaust gas temperature vs engine speed for 9˚ SOI, 45˚ IVO and FIP-2



(a)

(b)

Figure 15. (a) NO_x emission and engine torque vs engine speed for 7˚ SOI, 45˚IVO, swirl-2 cylinder head, and FIP-2; (b) CO emission and exhaust gas temperature vs engine speed for 7˚ SOI, 45˚IVO, swirl-2 cylinder head, and FIP-2

Various strategies produced different results for engine performance and emission under full throttle performance. Each strategy has specific advantages and disadvantages compared to the baseline engine. These strategies show the maximum possible improvement for performance and reduction in various emission parameters under operating conditions. To further reduce emissions, we need to optimize combustion chamber geometry, external EGR, nozzles and intake ports for feeding more air.

5. CONCLUSIONS

Experimental tests were conducted on a single-cylinder naturally aspirated diesel engine to study the effect of valve timings, SOI and swirl ratio on its performance and emission characteristics. Previous studies focused on IVC timing and EGR for the reduction of NO_x emission, however, the present study is focused on the effect of IVO timing without EGR. The conclusions from the study are given below:

1. Advanced intake valve opening timing leads to higher valve overlap period and thus allows the backflow of exhaust gases into intake port and manifold which comes

back into the combustion chamber with fresh air and thus dilutes the oxygen availability in the fresh air.

2. This diluted air also helps in reducing NO_x emission as oxygen available for NO_x formation reduces and thus engine-out NO_x emission becomes lower. In the present study, engine-out emission reduced by 5-50% at different engine configurations at full throttle operating speed. Advanced IVO timing also helps in reducing in-cylinder and exhaust gas temperature.
3. The start of injection timing is an important factor affecting performance and emission as retarded SOI affects combustion rate, in-cylinder pressure, and temperature which directly affect CO, HC, and NO_x formation. In the present study, engine-out CO emission reduced by up to 50% for retarded SOI.
4. Cylinder head swirl and fuel injection pressure play a major role in in-cylinder fuel-air mixing and its uniform distribution. It also affects combustion characteristics due to pressure and temperature distribution inside the combustion chamber. Engine out NO_x emission is directly affected by swirl and injection pressure. Lower swirl strategy leads to NO_x reduction by 27%.
5. Retarded SOI, advanced IVO, and lower swirl strategy help in achieving lower NO_x and CO emission with torque improvement. This also helps in reducing exhaust gas temperature.
6. The developed strategies of SOI and advanced IVO with lower swirl can be utilized for the development of a multi-cylinder naturally aspirated engine for emission reduction. Previous studies have considered IVO with heavy exhaust EGR for reducing emission, however, a concrete solution is missing for naturally aspirated engines. Thus, this study would lead to a platform for the development of naturally aspirated engines with lower initial product cost and development time.

6. ACKNOWLEDGMENT

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Persian Abstract

چکیده

موتورهای دیزلی کوچک به دلیل نیازهای گشتاور بالاتر، صرفه‌جویی در مصرف سوخت و راندمان حرارتی بهتر، برای کاربردهای تجاری و وسایل نقلیه مسافربری بسیار مورد استفاده قرار می‌گیرند. این موتورها در معرض شرایط مختلف عملیاتی و محیطی قرار دارند و از این رو انتشار این موتورها نامناسب است. استراتژی‌های لازم برای افزایش کارایی و کاهش انتشار موتور با توجه به آلودگی محیط زیست و مقررات لازم است. هدف اصلی از این مطالعه تجربی، تدوین استراتژی‌هایی برای بهبود عملکرد و کاهش انتشار موتور برای موتورهای دارای فشار طبیعی است که می‌توان از آنها برای کاهش انتشار موتور چندسیلندر استفاده کرد. کار تجربی بر روی یک موتور دیزلی تک سیلندر انجام شده است تا تاثیر پارامترهای عملیاتی موتور مانند زمان سوپاپ، نسبت چرخش و فشار تزریق بر عملکرد موتور و تولید گازهای گلخانه ای بررسی شود. پارامترهای در نظر گرفته شده برای مطالعه عبارتند از: سه زمان باز کردن شیر ورودی، دو فشار پمپ تزریق سوخت، چرخش سر دو سیلندر و سه شروع زمان تزریق. نتایج نشان‌دهنده بهبود عملکرد، کاهش دمای گاز اگزوز و کاهش انتشار موتوراست. دمای گازی اگزوز ۵–۱۸٪ با باز شدن دریچه پیشرفته و چرخش سر سیلندر کمتر، کاهش می‌یابد. میزان انتشار NOx در حالت IVO (میزان باز شدن شیر مکش) پیشرفته با SOI (شروع تزریق) کم شده و چرخش کمتر سرسیلندر، ۵–۵۰٪ کاهش می‌یابد. این موجب کاهش انتشار گازهای CO و HC می‌شود چرا که دسترسی به هوای تازه به دلیل EGR (چرخش گاز اگزوز) داخلی بالاتر، کمتر است. پمپ تزریق سوخت با فشار بالاتر با تأثیر منفی بر انتشار NOx موتور، در بهبود گشتاور موتور کمک می‌کند. از آنجا که این موتورها از قطعات ظرفیت پایین برخوردار هستند و در معدود کشورها مورد استفاده قرار می‌گیرند، تحقیقات در مورد این موتورها محدود است. کلیه کارهای تحقیقاتی در زمینه زمانبندی بستن دریچه ورودی، زمان نسبت چرخش و زمانبندی تزریق انجام شده است. با این وجود تحقیقات بسیار محدودی در مورد اثر زمانبندی باز کردن دریچه ورودی موجود است که این مساله به محدودیت فاصله شیر پایین و پیستون در موتورهای دیزلی مربوط می‌شود.