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

A. Jain*, E. Porpatham†, S. S. Thipse* 

*The Automotive Research Association of India, Pune, India
†Vellore Institute of Technology University, Vellore, India

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. NOx 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 NOx 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.

doi: 10.5829/ije.2020.33.08b.19

NOMENCLATURE

Abbreviations

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

1. INTRODUCTION

Small diesel engines are widely used for commercial vehicle and passenger car applications in Asia. Its fuel economy along with minimum operational and maintenance cost make it more popular for urban and
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\textsubscript{x} emissions which are among the major sources of environmental pollution. Stringent emission norms are brought by the government to curb these emissions 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\textsubscript{x} formation in diesel engines is mainly attributed to engine thermal management which increases 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\textsubscript{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\textsubscript{x} emissions with 3 IVC strategy. They concluded that a low level of NO\textsubscript{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\textsubscript{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\textsubscript{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\textsubscript{x} emission. Results showed that NO\textsubscript{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\textsubscript{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\textsubscript{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
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 NOx 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.

| Type                | Four strokes, air-cooled, single-cylinder, CI engine |
|---------------------|-----------------------------------------------|
| Fuel                | Diesel                                        |
| Number of cylinders | One                                           |
| Bore/Stroke         | 1146                                          |
| 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       |

2. EXPERIMENTAL TEST SETUP

Experimental work has been carried out on air-cooled four-stroke single-cylinder direct injection diesel engine...
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@200 rpm with engine out exhaust gas temperature of 672°C. NOx 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 NOx emission by 15% for max torque speed, however, rated speed NOx 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 SENSIFLOW-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         | ±0.05           |
| 5      | Emission analyzer              | AVL Emission Test Systems, Germany-AVL AMA 60-03 | CO: ± 0.07% of full-scale reading | ± 3.92          |
|        |                                |                                  | NOx: ± 0.53% of full-scale reading|                 |
|        |                                |                                  | THC: ± 0.53% of full-scale reading|                 |
| 6      | Torque speed                   | Benz Systems, India              | ± 0.25% of full-scale reading     | ± 2             |
| 7      | PM measurement                 | AVL Emission Test Systems, Germany-AVL 472-04(A) | ± 0.5% of full-scale reading | ± 0.5          |
| 8      | Smoke                          | AVL Opcometer439-05             | ±0.53% of full-scale reading      | ± 3.9           |
| 9      | Charge amplifier               | KISTLER, Switzerland            | ± 0.25% of full-scale reading     | ± 0.9           |
| 10     | Crank angle encoder            | AVL, Austria                     | ± 1% full-scale reading           |                 |
| 11     | Digital data acquisition system | AVL Puma Graz, Austria          | ± 0.1°C                          | ± 2 bit         |
| 12     | Thermocouple (K-type)          | HI-TECH Transducers & Devices, India | ± 0.75% of full-scale reading | ± 2             |
### TABLE 3. Test cluster and matrix

| 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                                                    |

Figure 2. (a) NOx 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

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

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 NOx formation and this is the main reason for higher NOx 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 NOx emission, however, diluted air reduces the oxygen
availability and hence reduces NOx 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 NOx 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 NOx emission as limited oxygen is available for NOx 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 NOx 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

Figure 4. (a) NOx 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

Figure 5. (a) NOx 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 atomization. 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 NOx 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 NOx 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.

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

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

Figure 7. (a) NOx 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
Retarded SOI of 9° with advanced IVO of 45° bTDC, baseline FIP, and cylinder head reduces NOx emission by 6%. Rated speed NOx is reduced by 32%, however, max torque-speed NOx 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 NOx 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 NOx 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

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

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 NOx 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 NOx emission by 6%. Rated speed NOx is reduced by 32%, however, max torque-speed NOx 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 NOx 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 NOx 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
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 NOx 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.
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 NOx 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 NOx 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](image1)

![Figure 14. CO emission and exhaust gas temperature vs engine speed for 9° SOI, 45° IVO and FIP-2](image2)

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 NOx 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 NOx emission as oxygen available for NOx formation reduces and thus engine-out NOx 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 NOx 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 NOx emission is directly affected by swirl and injection pressure. Lower swirl strategy leads to NOx reduction by 27%.
5. Retarded SOI, advanced IVO, and lower swirl strategy help in achieving lower NOx 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

The authors would like to thank HoD and department staff of the Powertrain Engineering Department (PTE) of Automotive Research Association of India (ARAI), Pune, India for the support to carry out this research work.

7. REFERENCES

1. Knecht, W. “Diesel engine development in view of reduced emission standards.” Energy, Vol. 33, No. 2, (2008), 264–271. https://doi.org/10.1016/j.energy.2007.10.003
2. Taylor, A. M. K. P. “Science review of internal combustion engines.” Energy Policy, Vol. 36, No. 12, (2008), 4657–4667. https://doi.org/10.1016/j.enpol.2008.09.001
3. Agrawal, A. K., Singh, S. K., Sinha, S., and Shukla, M. K. “Effect of EGR on the exhaust gas temperature and exhaust opacity in compression ignition engines.” Sadhana - Academy Proceedings in Engineering Sciences, Vol. 29, No. 3, (2004), 275–284. https://doi.org/10.1007/BF02703777
4. Squillera, L. F. F., Martins, C. A., and Lacava, P. T. “Strategies for emission control in diesel engine to meet Euro VI.” Fuel, Vol. 104, (2013), 183–193. https://doi.org/10.1016/j.fuel.2012.07.027
5. Jafari, B., Khatamnezhad, H., Shahavi, M. H., and Ganjii, D. D. “Simulation of Dual Fuel Combustion of Direct Injection Engine with Variable Natural Gas Premixed Ratio.” International Journal of Engineering, Transactions C: Aspects, Vol. 32, No. 9, (2019), 1327–1336. https://doi.org/10.5829/ijte.2019.32.09c.14
6. Patnaik, P. P., and Acharya, S. K. “Effect of Compression Ratio on Emission of CI Engine using Neat Karanja Oil and Karanja Oil Methyl ester Blends.” International Journal of Engineering, Transactions C: Aspects, Vol. 27, No. 3, (2014), 403–410. https://doi.org/10.5829/idosi.ijte.2014.27.03c.07
7. Boussouara, K., Merabet, A., and Kadja, M. “Modeling of Combustion and Carbon Oxides Formation in Direct Injection Diesel Engine.” International Journal of Engineering, Transactions A: Basics, Vol. 25, No. 3, (2012), 211–219. https://doi.org/10.5829/idosi.ijte.2012.25.03a.03
8. Khatamnezhad, H., Khalilzadeh, A., Jafarpour, S., and Pourfallah, M. “Numerical Investigation on the Effect of Injection Timing on Combustion and Emissions in a DI Diesel Engine at Low Temperature Combustion Condition.” International Journal of Engineering, Transactions B: Applications, Vol. 24, No. 2, (2011), 165–179. Retrieved from http://www.ije.ir/article_71906.html
9. Zhang, X., Wang, H., Zheng, Z., Reitz, R. D., and Yao, M. “Effects of late intake valve closing (LIVC) and re-breathing valve strategies on diesel engine performance and emissions at low loads.” Applied Thermal Engineering, Vol. 98, (2016), 310–319. https://doi.org/10.1016/j.applthermaleng.2015.12.045
10. Zammit, J. P., McGhee, M. J., Shayler, P. I., Law, T., and Pegg, I. “The effects of early inlet valve closing and cylinder disablement on fuel economy and emissions of a direct injection diesel engine.” Energy, Vol. 79, No. C, (2015), 100–110. https://doi.org/10.1016/j.energy.2014.10.065
11. Wang, Y., Zeng, S., Huang, J., He, Y., Huang, X., Lin, L., and Li, S. “Experimental investigation of applying miller cycle to reduce NOx emission from diesel engine.” Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, Vol. 219, No. 8, (2005), 631–638. https://doi.org/10.1243/09576505SXX31289
12. Tomoda, T., Ogawa, T., Ohki, H., Kogo, T., Nakatani, K., and Hashimoto, E. “Improvement of Diesel Engine Performance by Variable Valve Train System.” International Journal of Engine Research, Vol. 11, No. 5, (2010), 331–344. https://doi.org/10.1243/14680874ER856
13. Benajes, J., Molina, S., Martin, J., and Novella, R. “Effect of advancing the closing angle of the intake valves on diffusion-controlled combustion in a HD diesel engine.” Applied Thermal Engineering, Vol. 29, No. 10, (2009), 1947–1954. https://doi.org/10.1016/j.applthermaleng.2008.09.014
14. Deng, J., and Stobart, R. “BSFC investigation using variable valve timing in a heavy duty diesel engine.” In SAE Technical Papers. SAE International. https://doi.org/10.4271/2009-01-1525
15. Ghaifor, M., Kakaei, A. H., and Mashadi, B. “Semi-empirical modeling of volumetric efficiency in engines equipped with variable valve timing system.” Journal of Central South University, Vol. 23, No. 12, (2016), 3132–3142. https://doi.org/10.1007/s11771-016-3379-3
16. Sürmen, A., Arslan, R., Kompaz, O., Avci, A., Karagöz, I., and Karamangül, M. I. “Development of a variable-profile cam to enhance the volumetric efficiency of IC engines.” International Journal of Vehicle Design, Vol. 73, No. 1, (2017), 63–75. https://doi.org/10.1504/IJVD.2017.082581
The effects of late intake valve closing and different cam profiles on the in-cylinder flow field and the combustion characteristics of a compression ignition engine.