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# NUMERICAL SIMULATION OF $NO_X$ & SOOT EMISSIONS OF SINGLE CYLINDER DIESEL ENGINE WITH EGR MODIFIED TO RUN ON CRDI FOR HIGH PRESSURE SPLIT INJECTIONS

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*Abstract*

High pressure split injection with advanced fuel injection strategies is one of the prominent techniques for controlling the emissions NOx and Soot released from diesel engines however Exhaust gas recirculation (EGR) is one of the significant methods to control the engine emissions but research is limited for high pressure fuel injection technique. Various injection strategies like advanced and retarded injection angles are well known but proper published results for high pressure fuel injection is not available. At the same time these advanced injection strategies can control the injection pressure and fuel injection duration angle but nozzle orientation is fixed and cannot be changed frequently due to the manufacturing limits. Also, the choice of the fuel injection angles is trial based and hence accurate prediction of the engine performance is very much limited. To overcome this draw back numerical simulations using converge CFD software is performed for single cylinder diesel engine for EGR flow rates ranging from 0-15% on mass basis for 250bar injection pressure. The simulation results show that that 5% EGR flow rate for -11deg @250 bar fuel injection angle at injection pressure is effective in reducing the NOx and Soot emissions efficiently when the engine run on ULSD diesel fuel with cooled EGR.

Keywords: CI Engine, EGR, SOI, CONVERGE, Ultra low sulphur diesel

## 1.Introduction

CI engines are preferred over SI engine, because of their higher efficiencies. However, $NO_x$ and soot emissions emitted from diesel engines cause serious environmental and health problems. These emissions increase global warming which results in creating problems such as rise in ambient temperatures, rising and flooding of oceans etc. 80% of the commercial vehicles are equipped with diesel engines. From the past, researchers have been focussing on reducing the emissions, but still the $NO_x$ and soot emissions from diesel engines still remain high. Selective catalyst reduction (SCR) is one of the emerging techniques in the present and the past. But the stringent emission and towering costs associated with these conversion devices made the automobile makers to focus more on bringing down the pollutants within the cylinder itself by modifying the engine design parameters (Jiang and Li, 2016).

Soot, which is also called as black carbon is generated from the incomplete combustion of hydrocarbons of the fuel. Soot among this particulate matter has been serious health hazard for human health (Omidvarborna et al., 2015). Liu *et al*., (2015) investigated the most effective method to reduce soot formation, by varying different operating parameters such as SOI, EGR and fuel injection pressure and found that advancing the fuel injection timing technique has more impact in reducing the soot emissions than fuel injection pressure and EGR. *Kouremenos* et al., (2001) investigated the sole effect of advanced injection (varied from 2 to 20$^o$ bTDC) and exhaust gas recirculation (varied from 0 to 30%) at different speeds and loads (25%, 50%, 100%). It is observed that, the use of EGR has resulted in increase of soot emissions, and while advancing the injection timings, it decreased simultaneously. Saravanana et al (2013) investigated the effects of three in-cylinder parameters: Fuel injection pressure, fuel injection timing and exhaust gas recirculation in which SOI was advanced and retarded by 2.5 deg from baseline case, EGR is varied in three levels (0%, 10%, 15%). The injection pressure is varied from 210 bar to 250 bar. Their results showed that EGR is the most impacting parameter for reduction of $NO_x$. Gunabalan et al. (2010) using CFD analysis showed that soot emission decreases with early injection and showed that peak pressure increased, when injection timing is advanced and $NO_x$ emission increased with advanced SOI (without EGR) and soot emission decreased with advanced SOI. Kashyap Chowdary et al., (2016) investigated the individual effects of SOI and EGR and combined effect of these parameters over a limited range. The $NO_x$ emissions were decreased by 1.2 % and soot emissions were reduced by 21% by advancing SOI by 3.5 deg and using EGR fraction of 10%. Ganji et al., (2016) studied the parametric optimization through numerical simulation on VCR engine using CONVERGE CFD to analyse the individual effects of different parameters such as SOI, Exhaust gas recirculation and Compression ratio. The variation of these parameters were able to achieve better $NO_x$ and soot emissions without compromising in the performance. Jayashankara and Ganesan (2010) studied the effect of fuel injection timing and intake pressure on performance of diesel engine using STAR-CD CFD code. SOI has been varied by (8, 12 and16 CA bTDC) and intake pressure by (1.21, 1.01 and 1.71 bar) and showed that increasing trend is observed in $NO_x$ as the injection timing is advanced and in case of soot, increased till certain crank angle and then showed reverse trend.

Response surface methodology is a technique to optimize the output parameters of a multi objective function. Response surface methodology has been widely applied in number of applications in the manufacturing fields for the design and development of new products, as well as in enhancing the existing design of the products (Han et al., 2014; Rout et al., 2014). Pandian et al., (2001) used RSM method to optimize and analysed the effect of injection parameters like injection pressure, injection timing and nozzle tip protrusion on the performance and emission characteristics of a twin cylinder CI engine and obtained a desirability of 0.98 at the optimum injection parameters of 225 bar injection pressure, 21$^o$ BTDC of injection timing and 2.5 mm of nozzle protrusion.

From the above research findings published earlier it can be observed that many researchers have done lot of work available for CFD analysis on I.C engines aimed at reducing the emissions, but lacks in discussion about interaction effect of both SOI and EGR. In this work, the combined effect of advanced Start of Injection (SOI) and Exhaust Gas Recirculation (EGR) on performance and emissions of DI CI engine has been analysed, using CONVERGE$^{TM}$ (CFD) code and validated with experimental data from (Curtis et al., 1995).

## 2. Experimental setup

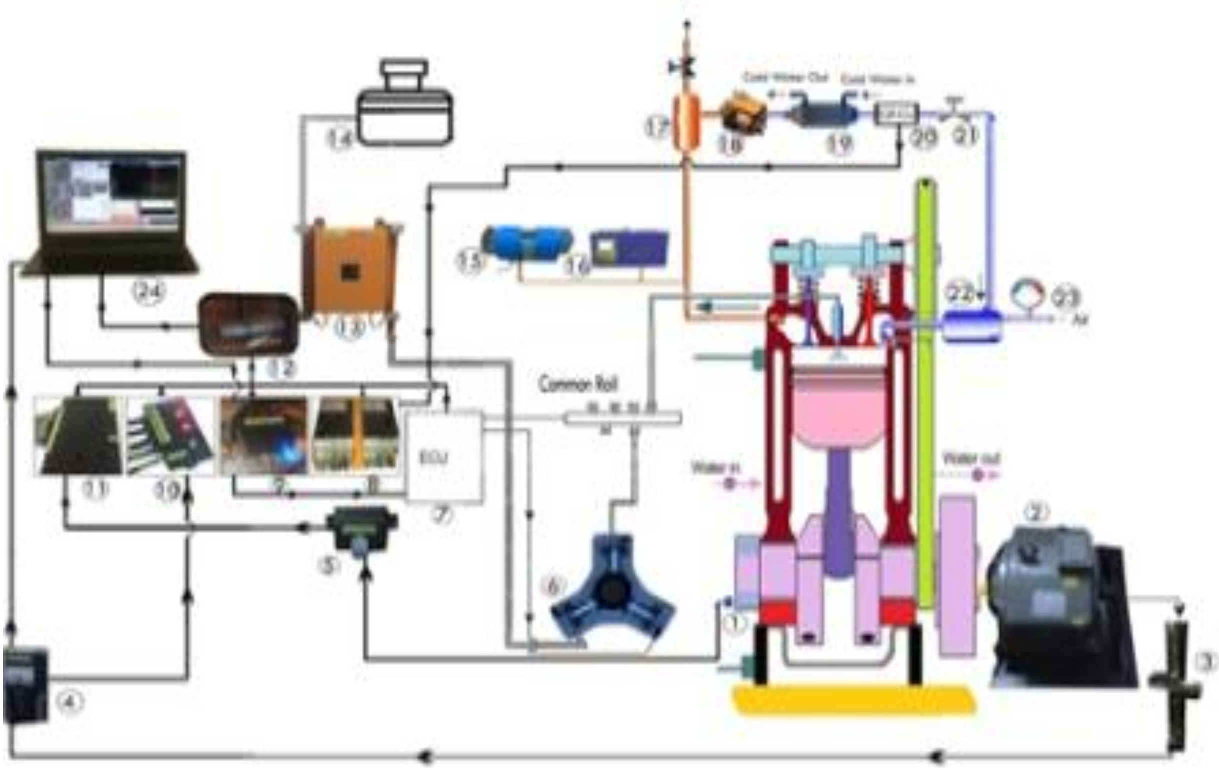


**Figure 1:** Schematic Layout of Experimental Setup

**Figure 2:** Engine Test Facilities

### 3. Engine simulation and computational domain

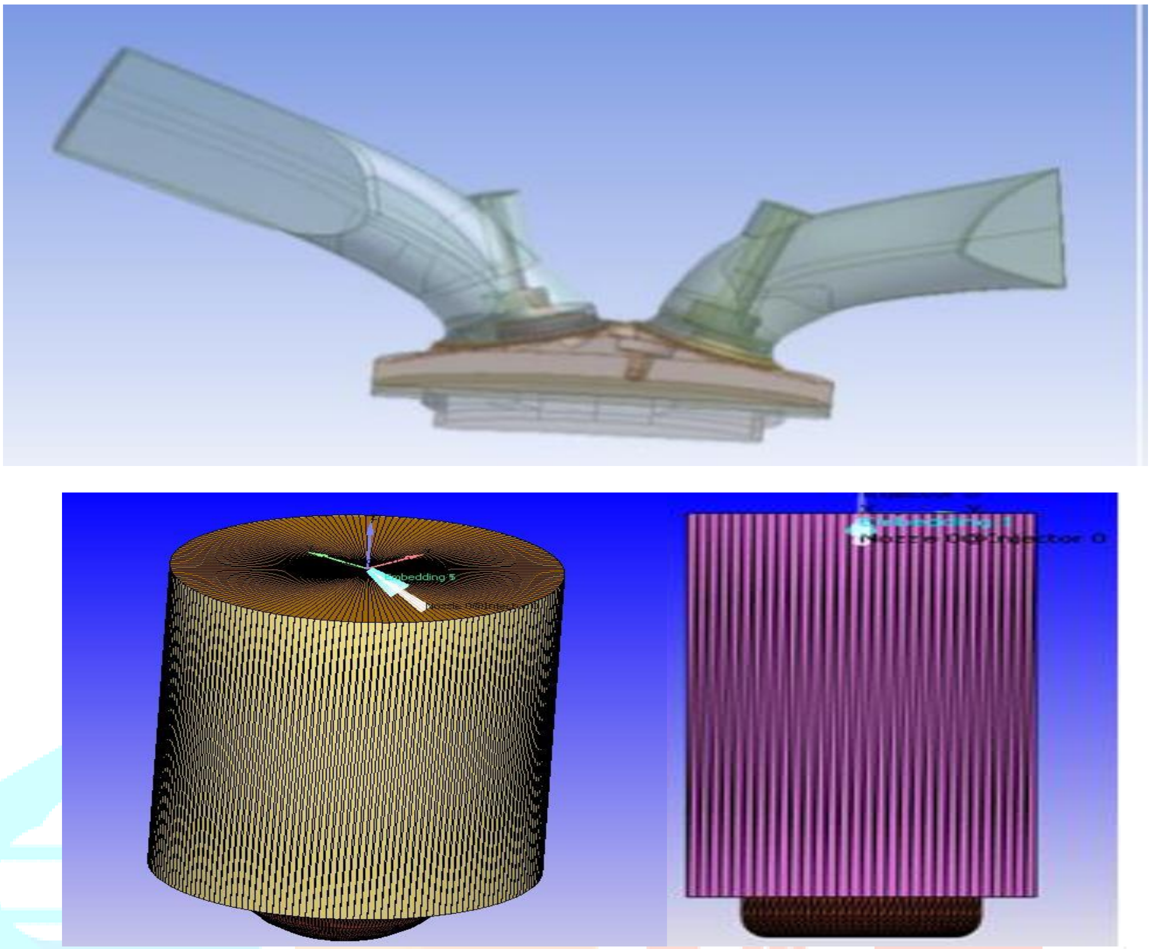

**Figure 3: CAD Model of Drawing**

### 4.Methodology and computational domain

The CFD simulation has been carried out on a single cylinder direct injection Kirloskar diesel engine containing Mexican hat bowl profile. The CFD code used in this simulation is CONVERGE$^{TM}$. Make surface utility command in CONVERGE is used to design the entire computational domain and Post processing work is done on ENSIGHT. The computational mesh applied on the domain is employed with 2,50,000 cells. Adaptive Mesh Refinement (AMR) is used during the simulation to automatically refine the grid based on fluctuating and moving conditions, such as temperature and velocity. The baseline parameters are considered to be SOI 11$^{o}$ BTDC and EGR 15%.

As it is generally perceived that, the combustion process occurs during the compression and expansion process. And since as the present analysis is focused on the emissions at the end of combustion, simulation is carried till the exhaust valve opening. The simulation of the model is run from 147$^{o}$ BTDC (i.e Inlet valve closure) to 150$^{o}$ ATDC (i.e Exhaust valve opens). The Kirloskar diesel engine employs 3 orifice nozzles at spray angle of 30$^{o}$. An axi-symmetric sector of 120$^{o}$ engine geometry, as shown in Figure 1 (different views of the model), is used to reduce the computational time instead of 360$^{o}$ model. 360/3= 120 (3 equal sector models can be created, each sector model is considered to have one nozzle hole).

**Boundary conditions & Initial conditions:**

The initial and boundary conditions of the simulation model used in CONVERGE CFD code are stated in table 2.

**Table:1 Engine specifications**

| 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@ 1500rpm |
| 5 | Engine speed | 1500rpm |
| 6 | Fuel | Diesel |
| 7 | Bore & Stroke | 80 X 110 mm |
| 8 | Displacement | 553E-6m$^3$ |
| 9 | Compression Ratio | 16.5:1, Range: 13.51 to 20 |
| 10 | Injection Pressure | 230 bar-350bar |
| 11 | Cylinder Pressure | Piezo Sensor, Range: 200 psi |
| 12 | Nozzle | 3 holes, Ø0.15 mm |
| 13 | Dynamometer | Eddy current dynamometer |
| 14 | Orifice Diameter | 20 mm |

**Table 2:** Boundary conditions and Initial conditions of incorporated during simulation.

| | |
|---|---|
| Inlet air pressure | 1.97 bar |
| Overall equivalence ratio | 0.46 |
| Inlet air temperature | 303 K |
| Cylinder wall temperature | 433 K |
| Piston wall temperature | 553 K |
| Head temperature | 523 K |
| Initial gas temperature | 365 K |
| Spray temperature | 341 K |

## *5. Emissions Modelling*

### *5.1 $NO_x$ Model*

Extended Zel'dovich mechanism is used by CONVERGE in solving the $NO_x$ emissions formation and it was formulated by Heywood (1988). The set of mechanism reactions are as follows:

$$O + N_2 \Leftrightarrow NO + N \quad (1)$$

$$N + O_2 \Leftrightarrow NO + O \quad (2)$$

$$N + OH \Leftrightarrow NO + H \quad (3)$$

The rate constants of the following above equations (1,2,3) are as follows:

$$k_{R1f} = 7.6x10^{13} \exp\left(\frac{-38000}{T}\right) \quad (4)$$

$$k_{R1b} = 1.6x10^{13} \quad (5)$$

$$k_{R2f} = 6.4x10^9 Texp\left(\frac{-3510}{T}\right) \quad (6)$$

$$k_{R2b} = 1.5x10^9 Texp\left(\frac{-19500}{T}\right) \quad (7)$$

$$k_{R3f} = 4.1x10^{13} \quad (8)$$

$$k_{R3b} = 2.0x10^{14} exp\left(\frac{-23650}{T}\right) \quad (9)$$

where subscript 'f' denotes the forward reaction and 'b' denotes backward reaction.

***5.2 Soot model (Hiroyasu-NSC)***

Empirical Hiroyasu Soot model which is coupled with Nagle and Strickland-Constable model (NSC) is used to model the soot in the computational domain. Soot and particulate matter formation are mainly responsible due to improper combustion in the cylinder.

The production of soot mass $M_s$ (g) can be determined in a single-step equation between the soot mass formation rate $M_{sf}$ (g) and the soot mass oxidation rate $M_{so}$ (g) according to Hiroyasu and Kadota (1976).

$$\frac{dM_s}{dT} = M_{sf} - M_{so} \quad (10)$$

And the rate of formation is given by

$$M_{sf} = SF.M_{form} \quad (11)$$

$$SF = A_{sf} P^{0.5} \exp\left(\frac{-E_{sf}}{R_u T}\right) \quad (12)$$

$M_{form}$ is the mass of soot formation species,

$P$ is the cell pressure,

$R_u$ is the universal gas constant in cal/(Kgmol),

$T$ is the cell temperature in K,

$E_{sf}$ is the activation energy in cal/gmol and

$A_{sf}$ is the Arrhenius pre-exponential factor.

Nagle and Strickland-Constable model (1962) model considers carbon/soot oxidation by two mechanisms reactions. This mechanism involves greater reactive areas 'A' and lesser reactive areas 'B'. The net reaction $R_{total}$ given by

$$R_{total} = \left(\frac{K_A P_{O_2}}{1+K_Z P_{O_2}}\right) X + K_B P_{O_2}(1-X) \left(\frac{mol}{cm^2 s}\right) \quad (13)$$

Where X is given by

$$X = \frac{P_{O_2}}{P_{O_2}+\left(\frac{K_T}{K_B}\right)} \quad (14)$$

$P_{O_2}$ is the oxygen partial pressure in atmospheres and the K values

are rate constants for carbon shown as follows

$$K_A = 20 \exp\left(-\frac{30,000}{R_u T}\right) \left(\frac{mol}{cm^2 s} atm\right) \quad (15)$$

$$K_B = 4.46\ x\ 10^{-3} \exp\left(-\frac{15{,}200}{R_u T}\right) \quad \left(\frac{mol}{cm^2} s\ atm\right) \tag{16}$$

$$K_T = 1.51\ x\ 10^{5} \exp\left(-\frac{97{,}000}{R_u T}\right) \quad \left(\frac{mol}{cm^2} s\ atm\right) \tag{17}$$

$$K_Z = 21.3 \exp\left(\frac{4{,}100}{R_u T}\right) \quad \left(\frac{1}{atm}\right) \tag{18}$$

The rate of soot oxidation according to Nagle Strickland-Constable oxidation model is given by:

$$M_{so} = A_{so}.\left(\frac{6M_s}{\rho_s\ D_s}\right) R_{total}\ MW_c \tag{19}$$

## 6. Results and discussion

**$NO_x$ emissions:**

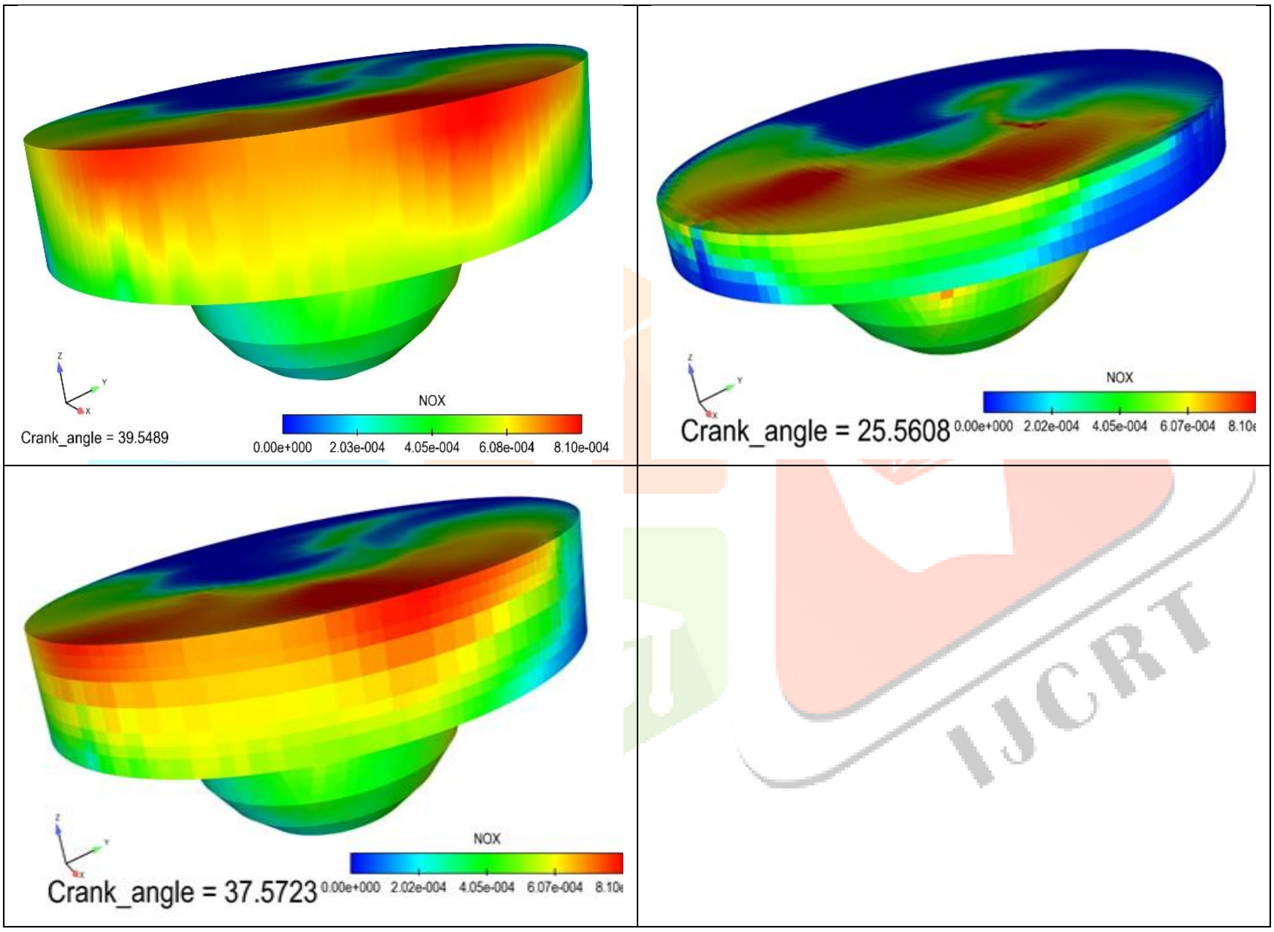


**Figure 4: $NO_x$ emissions for various crank angles.**

The emission of NOx is directly linked to the content of oxygen. As the temperature reaches a certain value, the development of NOx is initiated and the NOx formation increases much further. Figure 4 display $NO_x$ emissions for various crank angles**.** Soot emissions increased as NOx emissions decreased as expected with increased EGR. Increased EGRs do not decrease soot or NOx pollution substantially.

**SOOT Emissions:**

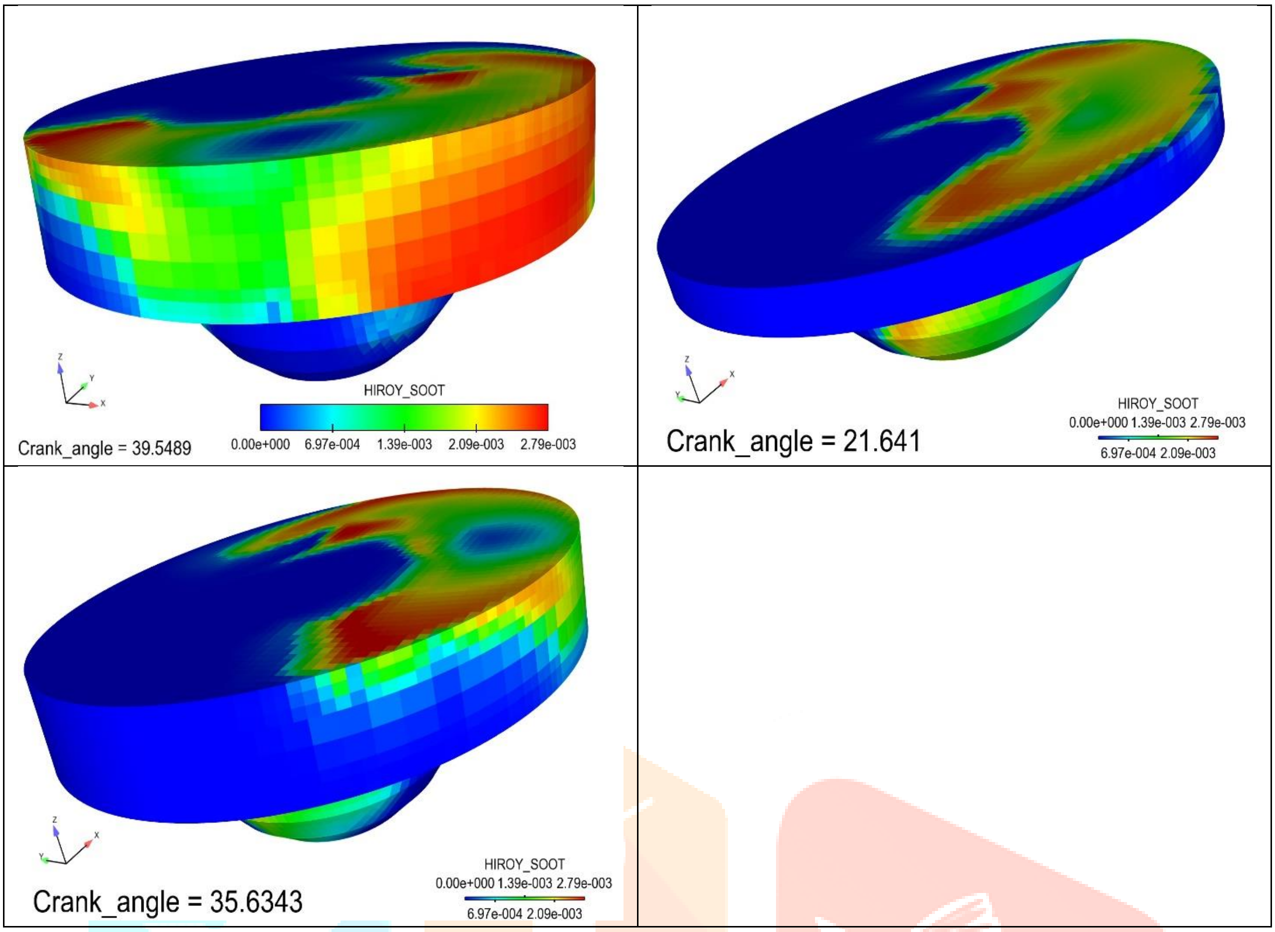


**Figure 5: SOOT emissions for various crank angles.**

The soot displays close to Figure 4, but 10% of EGR is seen in Figure 5. A combination of the two data sets shows clearly that improvements in the supply of oxygen and temperature are the key reason why EGR is affecting combustion. Thus, according to the observations of Ladommatos et.al., the key influence of EGR is to lower oxygen flow.

The soot generated has a strong oxidation rate at 15% EGR. Soot emissions are therefore poor. The elevated soot concentrations at high EGRs were believed to be attributed to lower local in-cylinder temperatures rather than increased soot formation. Soot oxidation levels are reduced in the soot stage of the soot. As EGR continues to rise, soot output will decrease sharply and the soot level will fall quickly. For temperature rises much more steeply than with adjustment in the equivalence ratio, soot emissions change. The shown reduction in soot pollution is a result of low temperature burning since the supply of oxygen is low.

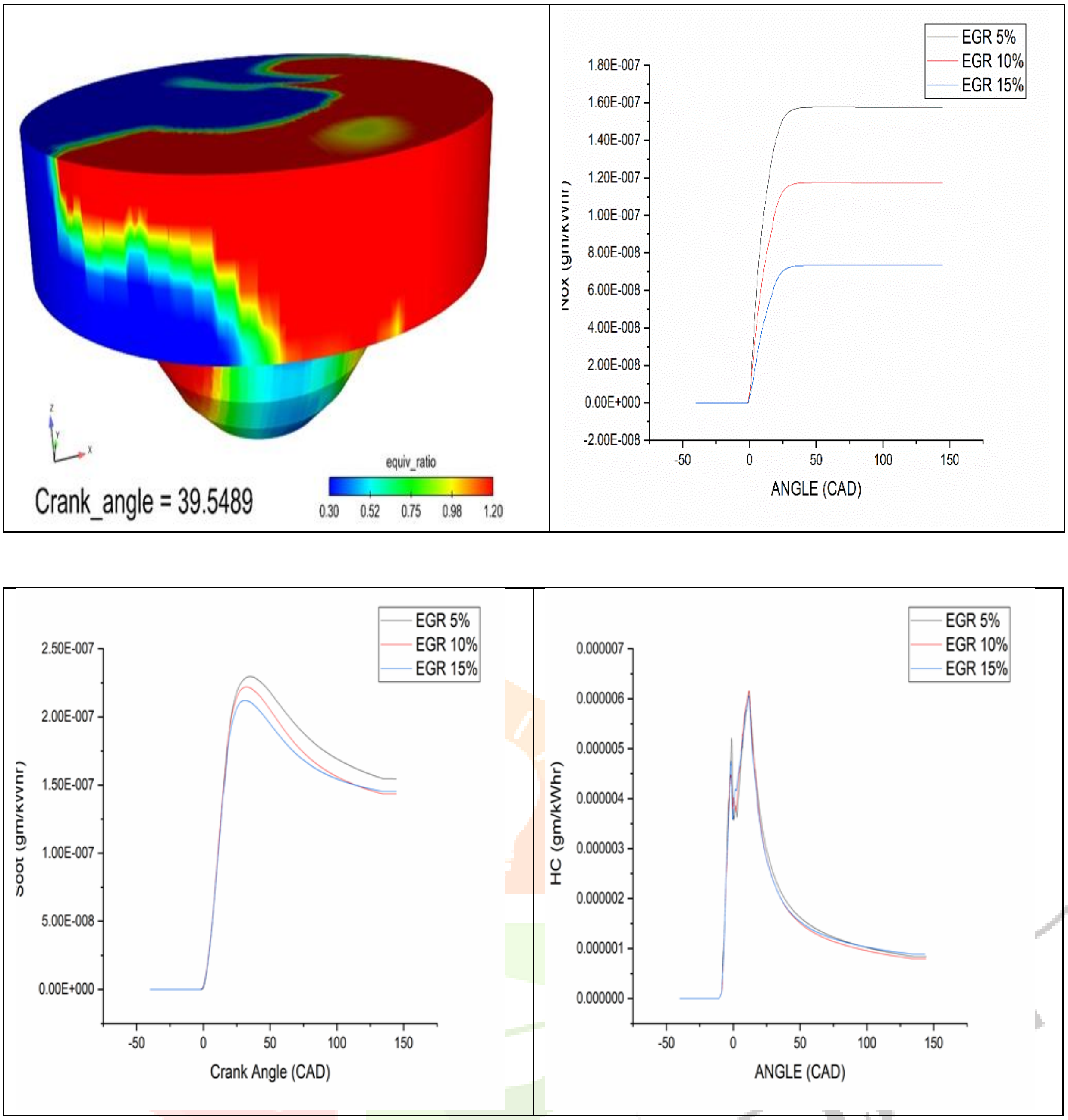


**Figure 6: Graphs for NOX ,SOOT ,HC for EGR 5%,10 % and 15%**

## Conclusions

In the present work, an effort has been made through simulation studies to modify two of the engine operating parameters (SOI & EGR) to achieve minimum $NO_x$ and soot emissions without a compromise in engine performance. software simulations have been run on CONVERGE for 3 different EGR flow rates ranging from 5% -15%. The results obtained from the simulation of optimised case suggest that models developed were quite accurate.

The following conclusions are drawn from the present study:

- EGR. flow rates show greater impact on $NO_x$ and soot emissions
- Higher EGR flow rates for SI combustion i.e., 10%SI reduced the soot formation and oxidation
- Injection pressure 250bar for SI mode with 10% EGR rates is effective in reducing the $NO_x$ emissions
- When cooled EGR is circulated further reduction in $NO_x$ is observed from 400ppm to 200ppm
- Increase in EGR rate from 5% 10% shows that air fuel ratio decreases by 20%
- Thus, in general it can be concluded that SI injection is suitable for high EGR flow injection pressures for single cylinder diesel engine modified to run on CRDI.

- Finally ,the conclusion is the EGR 5% is more advantageous in comparison with EGR 10 % and EGR 15 %.

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