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Combustion and Emission Characteristics of a Direct Injection Diesel Engine at Various EGR Conditions- A Numerical and Experimental Study

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ABSTRACT

Exhaust gas recirculation (EGR) is widely adopted to reduce the oxides of nitrogen (NOx) emission. This involves recirculation a controllable proportion of the engines exhaust back into the intake air. Present experimental study has been carried out to investigate the effect of EGR on performance and emission characteristics in a direct injection diesel. A Computational Fluid Dynamic (CFD) stimulation has been carried out in order to evaluate the effect of EGR and preliminary studies are carried out to validate the model with the experiment. For the computational analysis extended coherent flame model- 3 zone (ECFM-3Z) model of STAR-CD is considered. This model is suitable to analysis the combustion process in spark ignition (SI) and compression ignition (CI) engines. From the stimulation studies it is found that oxides of nitrogen decreases but soot increases due to lowered oxygen concentration.

Keywords: Computational Fluid Dynamics, Direct Injection, Emission, Exhaust Gas Recirculation

INTRODUCTION

A widely adopted route to reduce NOx emissions is Exhaust Gas Recirculation (EGR). EGR is a well adopted route to reduce NOx emissions in modern engines. It involves the process of recirculating a controllable proportion of engine's exhaust back into the intake air supplied into the cylinder. We control the flow of gas with the help of a valve that may be closed completely if required. When we substitute the burnt gas (which cannot take part in further combustion) for air which is rich in oxygen will reduce the proportion of the contents available in the cylinder for combustion. This will cause in the reduction in heat release and peak cylinder pressure to lower values and at the same time will reduce the formation of NOx. The inert gases present inside the cylinder will further reduce the peak temperature inside the cylinder. The gas which has to be recirculated also gets passed through an EGR cooler usually of the water type. This will reduce the temperature of the gas which reduces the cylinder charge temperature when EGR is been implemented. EGR can have two benefits-the reduction in the charge temperature which will result in lowering the peak temperature and the greater density of the cooled EGR gas allows a higher proportion of EGR to be used. In the case of a CI engine the recirculated fraction may as high as 50% under certain operating conditions.

In this work, the EGR percentage is varied in the case of a CI engine maintained at a constant RPM using extended coherent flame model of 3-zones with the help of CFD. The three zones are unmixed fuel zone, mixed gas zone, unmixed air plus EGR zones. Lean fuel operation and high compression ratio favour diesel engines to result in high thermal efficiencies. The high compression ratio produces the high temperatures required to achieve auto-ignition, and the resulting high expansion ratio makes the engine discharge less thermal energy in the exhaust. The extra oxygen in the cylinders is necessary to facilitate complete combustion and to compensate for non-homogeneity in the fuel distribution. Although simultaneous advantage between power and emission cannot be obtained, trade-off between the power output and the NOx emissions is better achieved using controlled feedback injection timing [1] mainly in compression ignition engines. The time period between the spray of diesel fuel and actual start of combustion is generally referred as ignition delay period. This ignition delay period is a crucial task during experimental investigation of diesel engines. The study of these processes by experimental approach involves expensive instruments with high level of skill and moreover, consumes a lot of time. Nowadays computational techniques evolved such that modelling these processes can contribute to better understanding of spray penetration, combustion and pollutant formation.

A eulerian-lagrangian spray and atomization model for diesel sprays was proposed successfully by Reitz & Diwakar [2]. Their numerical study on internal flow characteristics for a multi-hole fuel injector gives better agreement with the available experimental data. This indicates the capability of numerical model for studying diesel spray characteristics. Magnussen *et al* [3] developed a model based on the eddy break-up concept. This model relates the combustion rate to the eddy dissipation rate. This model expresses the rate of reaction by the mean mass fraction of the reacting species, the turbulence kinetic energy and the rate of dissipation. The spray penetration in the combustion chamber by accompanying different spray droplet break up due to instability was performed by Hossainpour and Binesh [4]. The spray calculations are based on statistical method referred as discrete droplet method. The results are validated with the experimental data. Various models are studied [5-8] for optimizing the combustion processes by stochastic procedures. Swirl is varied by designing the intake port and shaping the piston bowl for re-entrant combustion. For combustion chamber of re-entrant effects, the turbulent kinetic energy is intensified at TDC of compression stroke due to the conservation of angular momentum. Combustion is efficient and leads to low soot and high NOx emissions. The effect of variation of injection timing in diesel engine was studied by Sayin & Canakci [9]. They found that NOx and carbon dioxide emissions increased while the unburned HC & CO emissions decreased when injection timing is advanced. Han *et al* [10] investigated numerically the multiple injections and split injection cases. They found that split injection reduces the soot significantly without the change in NOx emissions whereas multiple injections reduce NOx significantly. The numerical study on diesel engine Simulation with respect to injection timing and the air boost pressure was carried out by Jayashankara *et al* [11].

CFD MODELS

The combustion and pollutant formations are carried out in detail using a commercial CFD package, STAR-CD in modelling of flow field of continuous and dispersed phases. The solution is obtained from the set of governing equations, law of conservation of mass, momentum, energy and species in a three dimensional in-cylinder, transient and reacting flow systems in a direct injection Diesel engine.

Turbulence Modelling

The in-cylinder flow is turbulent in nature at all speeds and dimensions of the engine. It is necessary to model the turbulence to capture the properties of in-cylinder fluid dynamics.

Combustion & Ignition Models

The ECFM-3Z model [12] is a general purpose combustion model capable of simulating the complex mechanisms of turbulent mixing, flame propagation, diffusion combustion and pollutant emission that characterize modern internal combustion engines. It can also be used for in-cylinder analysis in a multi-injection environment and for multi-cycle simulations. '3Z' stands for three zones of mixing, namely the unmixed fuel zone, the mixed gases zone, and unmixed air plus EGR zone. The three zones are too small to be resolved by the mesh and are therefore modelled as sub-grid quantities. The mixed zone is the result of turbulent and molecular mixing between gases in the other two zones and is where combustion takes place.

Droplet Models

The entry of droplet form nozzles to the combustion chamber is at high velocity and it is being spread at the outer periphery. Reitz and Diwakar model [2] is used for the disintegration of the droplets. Gas inertia and the internal turbulence stresses generated in the nozzle is governed by Huh's model [13]. The framework of lagrangian approach is used for the formulation of Bai [14] spray impingement model in order to reflect the stochastic nature of the impingement process; a random procedure is adopted to determine some of the droplet post-impingement quantities. The distribution of sizes and velocities of secondary droplets resulting from a primary droplet splash is obtained from the model mentioned above.

Pollutant Formation Models

The concentration of NOx is low in most of these devices; therefore, it has little influence on the flow field. Also the time scale for NOx reaction [15] is larger than the time scale for turbulent mixing process and the heat releasing reactions. So the computations of NOx can be decoupled from the main reacting flow field predictions by identifying three different mechanisms for the formation of nitric oxide during the combustion of hydrocarbons, by the formation and emission of carbonaceous particles in a process that is often observed. Soot's are particulates, which are identified in flames and fires as yellow luminescence. Specified detailed reaction mechanisms for the gas phase chemistry and the formation, growth, oxidation of soot particles was used for modelling soot formation.

Manimaran *et al* [16] studied the formation of pollutant using extended coherent flame model for 3-zones. The consideration is made for three unmixed fuel zone, mixed gases zone, unmixed air plus EGR zone. An experimental study was conducted by Gosh *et al* on EGR operation for biodiesel [17]. They investigated the performance by varying the EGR percentage between 0-10%. Jaffar *et al* studies the performance of a three-cylinder diesel engine by considering EGR [18], they concluded that the EGR has a positive effect on the emission characteristics of the engine. Saravanan studied the effect EGR and advanced injection timing on combustion characteristics [19], a detailed study on the injection time, delay period, peak pressure.

COMPUTATIONAL METHODOLOGY

Mesh Generation

CFD simulation starts with the geometry of the piston bowl. The piston bowl shape is prepared using Solid Works 10 package. The meshing of the in-cylinder fluid domain is performed using ES-ICE (Expert System — Internal Combustion Engine) Pro-surf tool. In this study, a 120° sector mesh is considered due to symmetry nature of the in-cylinder domain and thereby the computational time can be reduced considerably. Negative volumes were checked at all locations between BDC and TDC. The meshed geometry of the moving fluid domain at TDC i.e. 720 deg CA is shown in Fig. 1 (for BDC) and Fig. 2 (for TDC) and contains almost tetrahedral cells near cylinder axis.

Boundary Condition

The boundary conditions involved in the in-cylinder fluid domain have to be supplied to facilitate the solution of energy and momentum conservation equations. The boundary of the domain consists of moving wall at the bottom, periodic zones at the sides, cylinder liner wall, cylinder head wall at the top, axis and the injector. Piston top wall is applied with the moving wall boundary condition. The velocity of piston wall is calculated using the engine speed, crank angle, connecting rod, and stroke length details. The other surfaces of the geometry are simply stationary walls i.e. no slip condition. The different temperatures obtained from experiments at various surfaces are listed in Table-1.

Convergence Criterion

The continuity, momentum, energy and species equations are solved for every time step with convergence requirement of 1E-05. In this numerical study, the transient simulation starts at 580°CA and ends at 800°CA. This is the crucial period of investigation towards combustion and pollutant formation. For every time step, convergence conditions have to be met for all the equations.

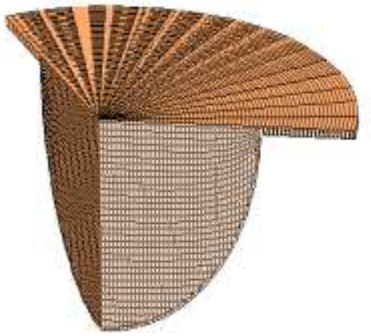


Fig.1 Computational grid with boundary surfaces at TDC at 720º CA

Fig.2 Computational grid with boundary surfaces at BDC at 800º CA

Table 1- Boundary Conditions

Boundary	Temperature
Combustion dome region	450K
Piston crown region	450K
Cylinder wall region	400K

Table 2-Models used in STAR-CD code

Phenomena	Model
Multi-Phase Treatment	Lagrangian
Droplet break up	Reitz-Diwarkar
Turbulence	I-L model
Combustion	ECFM-3Z Compression
Droplet wall interaction	Bai
Liquid Film	Angleberger
Atomization	Huh
Soot	Mauss
NOx mechanism	Hand,De Soete

Solver Details

The stimulation of droplet breaks up and spray droplet break up and spray penetration phenomena is activated using Lagrangian multiphase treatment. The turbulent dispersion model is included for the droplet to experience randomly varying velocity field in the cylinder. Collision model [20] is also considered to detect the collision of parcels for every time step. Gravitational force is also accounted on the droplet parcels. The number of droplet parcels considered in this work is exceeded beyond 50 million in numbers that enables to study the trajectory, spray penetration and collision physics. The flame surface density equation is solved by adopting extended coherent flame model for 3 zones namely, the unmixed fuel zone, the mixed gases zone and the unmixed zone of air together with EGR [12].

The complex mechanisms like flame propagation, diffusion combustion and pollutant formations were stimulated using ECFM-3Z combustion model, solver details are given in Table- 2. A small amount of exhaust gas is mixed with fresh air and then introduced into the combustion chamber. This modifies the fuel/air ratio and EGR, which lowers the peak temperature so that the chemical reaction rate between nitrogen and any unused oxygen is strongly reduced. Species concentrations involved in combustion reactions can .be written as a function of mixture fraction within the presumed probability density function model of combustion. Phenomenon and the model chosen were shown in Table-3. The liquid film model [21] accounts for convective transport of conserved quantities within the film and from/to the gas phase. Spray impingement model [14] is formulated within the framework of the Lagrangian approach to reflect the stochastic nature of the impingement process. A random procedure is adopted to determine the droplet post-impingement quantities. The standard pool boiling [22] is used to model liquid film boiling, when the wall temperature exceeds the saturation temperature of the liquid as the film starts to boil when the heat flux passes from the wall to the film. The injections of fuel start at 714° CA and ends at 722° CA.

Post-Processing

Time step computations are carried out till the residual values of the conservation equations of continuity, momentum and energy fall below 10-5. Auxiliary equations involving the turbulence spray models and models for combustion and emissions are also computed at every time step. The contours of the same quantities are also obtained by storing the information at pre-set crank-angles.

VALIDATION

To verify the results from the simulation, the pressure data computed is compared against experimental pressure data from a direct injection diesel engine. Table -3 shows the specification of test engine used. The 120° sector CFD model of experimental engine cylinder was modelled and a series of grid and time independency tests are carried out Crank angle step interval of 0.025° CA (i.e. 4.167 x 10^{-6} seconds) and mesh with 45000 cells (at TDC) are obtained as key information for further simulation from these tests. Validation of the current simulation work is carried out with the experimental pressure data of test engine. Fig. 3 shows the comparison of the simulation results with the experimental in-cylinder pressure under normal firing conditions. The computed in-cylinder pressure data from numerical simulation are in good agreement with the experimental data. The numerically simulated pressure values are in close agreement with the experimental data and the maximum deviation in peak pressure is less than 5%.

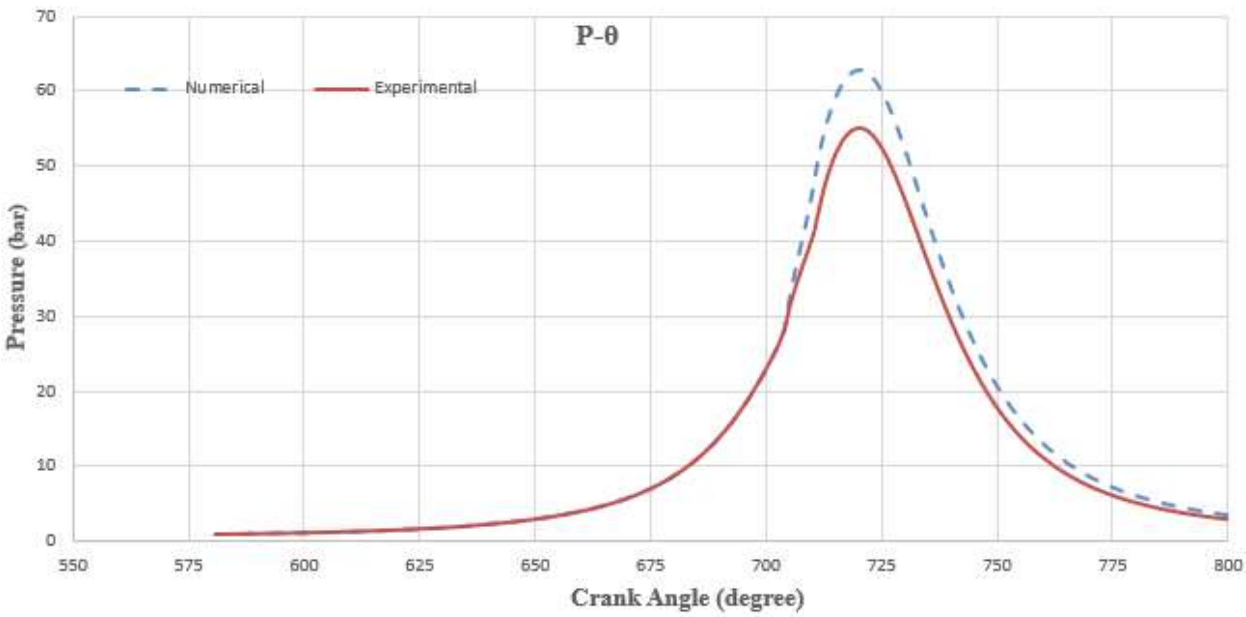


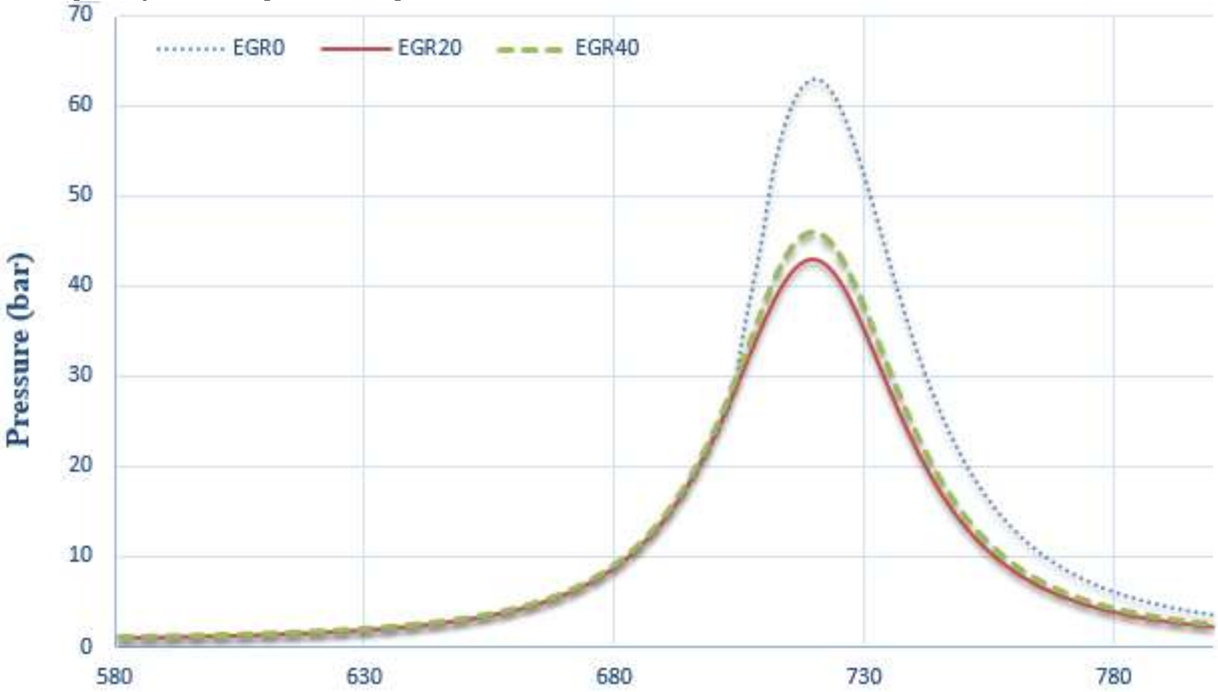
Fig.3 Comparison of numerical and experimental pressure date with CA

Table 3- Engine Specifications

Bore	0.080m	Fuel	Pure Diesel
Stroke	0.1m	Injector hole diameter	0.0004m
Compression Ratio	17	Injected mass	0.177kg/s
Connecting Rod Length	0.235m	Fuel-air equivalence ratio	0.85
Engine Speed	1500RPM		

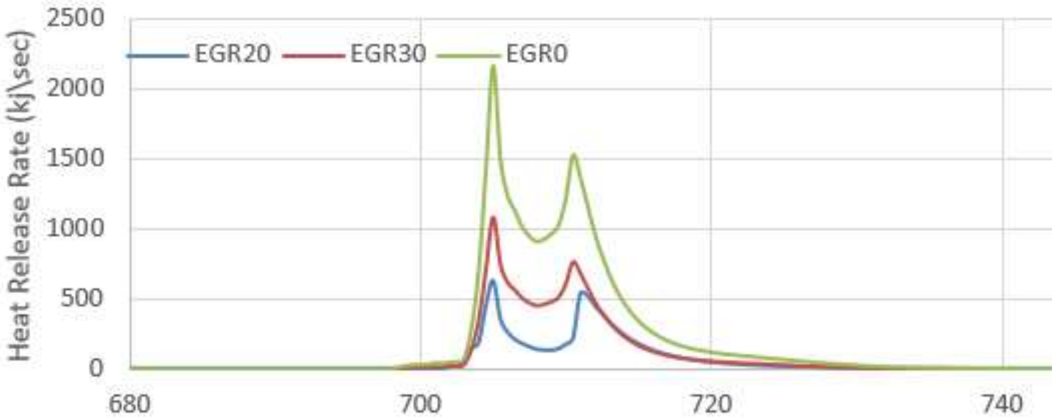
RESULTS AND DICUSSIONS

For the above mentioned geometry, in-cylinder parameters such as pressure, heat release rate, temperature and NOx are predicted numerically. EGR is varied from 0%-40%. This is normally achieved in a heavy duty direct injection diesel engine. At EGR=0% peak pressure obtained was 63 bar at 731°CA. At 20% EGR in-cylinder pressure drops to 46 bar and further drops to 42 bar at EGR=40%. This is due to the lowering of oxygen concentration in the inlet air and presence of EGR in the cylinder decrease the reaction as in Fig. 4 and Fig. 5 shows the heat release rate for different EGR conditions. Heat release rate reduces significantly as peak pressure reduces, that is at EGR=0% HRR is 2160 KJ/sec at 716° CA to 1080 KJ/sec at EGR=20% and hence further drops to 633 KJ/sec at EGR=40%. The in-cylinder temperature contour at different EGR condition is shown in Fig. 6, 7 and 8 at 800° CA. It can be observed that the peak cylinder temperature drops as the EGR is increased from 0% to 40%.



Crack Angle (deg)

Fig.4 Variation of pressure with CA at different EGR



Crack Angle (deg)

Fig.5 Variation of heat release rate with CA at different EGR

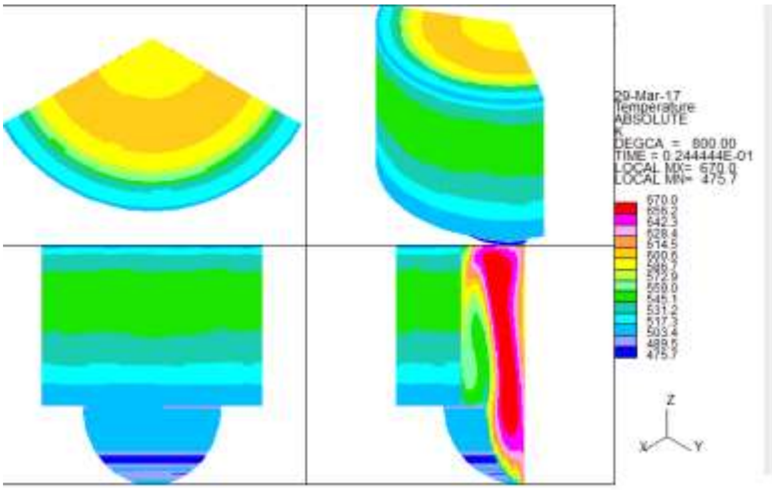


Fig.6 Contours of temperature (K) at EGR=0%

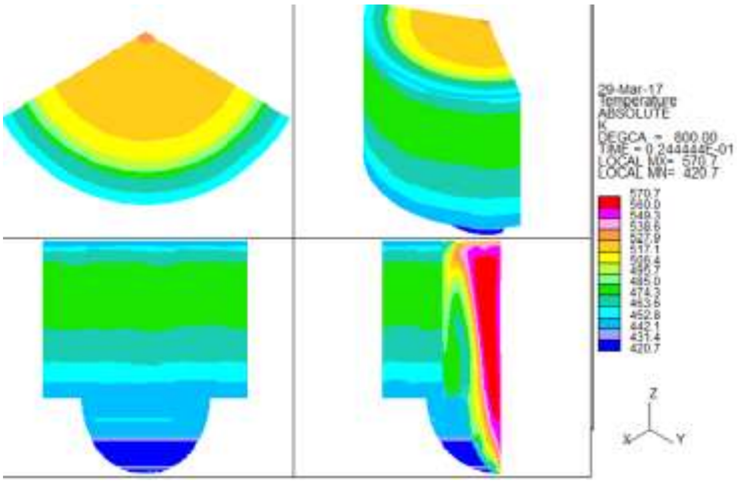


Fig.7 Contours of temperature (K) at EGR=20%

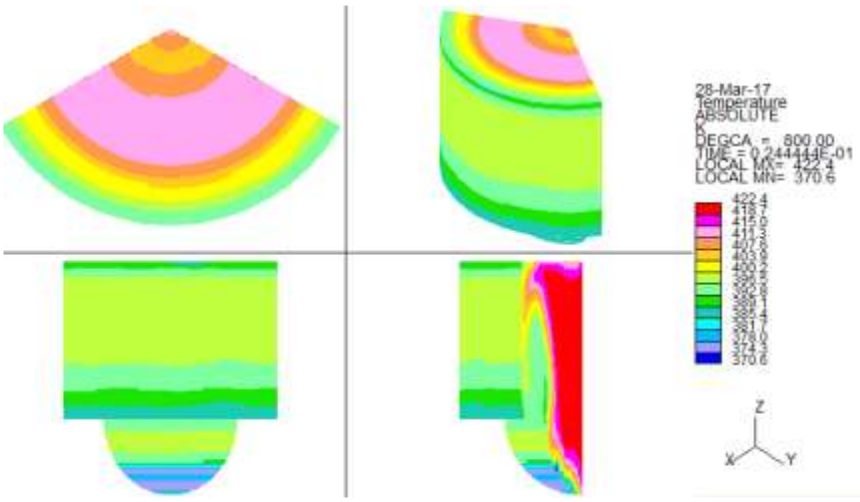


Fig.8 Contours of temperature (K) at EGR=40%

The variation of NOx at different EGR conditions are shown at Fig. 9, 10 and 11 at 800° CA. It is observed that reduction in nitrogen oxide levels as EGR percentage is increased due to the decrease in combustion temperature inside the cylinder.

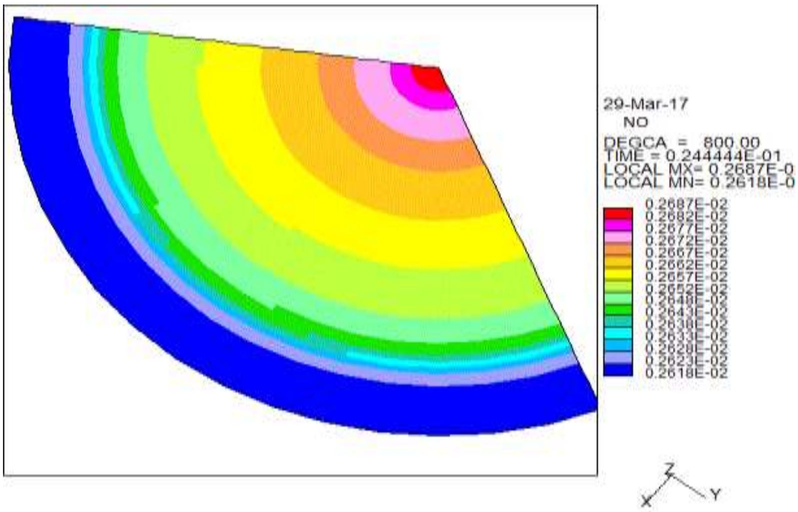


Fig.9 NOx at EGR=0%

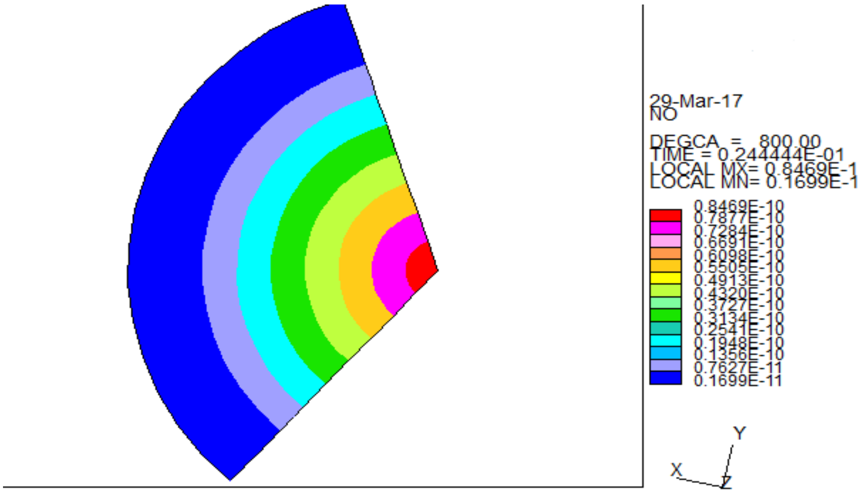


Fig. 10 NOx at EGR = 20%

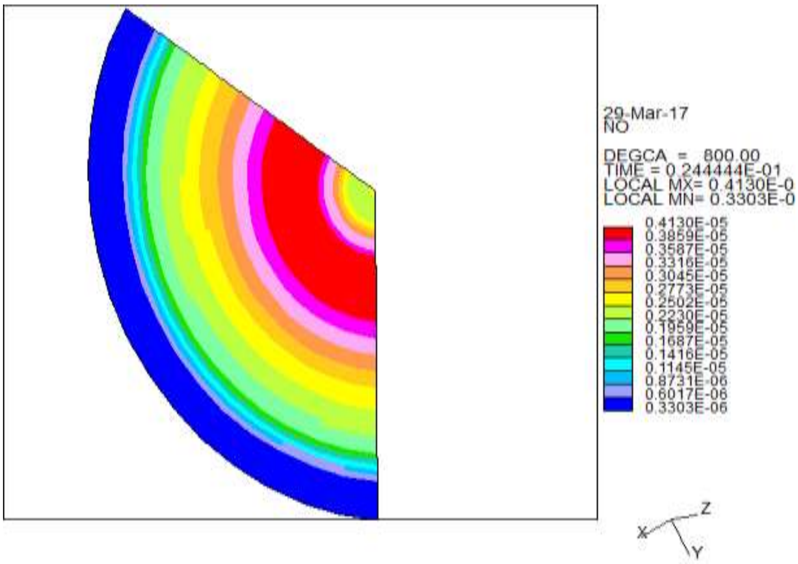


Fig. 11 NOx at EGR = 40%

CONCLUSION

Experimental and numerical investigation has been carried out to study the effect of Exhaust Gas Recirculation (EGR) on the performance of compression ignition engine. Different models governing the direct injection diesel engine combustion and pollutant formation are studied using simulation software. The results were compared with the experimental data and the following conclusions were drawn. There is a reduction in peak cylinder pressure observed with the increase of EGR. The peak in-cylinder pressure decreases by 21 bar when EGR is increased from 0% to 40%. The heat release rate follows the same characteristics as that of peak cylinder pressure, Heat release occurs nearly at 716-degree CA and deceases by 30% when the EGR is increased from 0% to 40%. Reduction in both in cylinder temperature and NOx formation were observed when EGR levels were increased. This is due to the fact that EGR admits the inert gases in the chamber which have specific heat higher than that of air so they absorb the heat of combustion and also dilute the fresh air which increases the ignition delay and hence reduce the heat of combustion which ultimately result in lower exhaust gas temperature and lower NOx emission. Exhaust gas recirculation (EGR) has been found a very effective way to reduce NOx emission from the diesel engine. EGR is still the most viable technique that can drastically reduce NOx to meet the emission regulations.

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