

NUMERICAL INVESTIGATION OF EFFECT OF EXHAUST GAS RECIRCULATION ON COMPRESSIONIGNITION ENGINE EMISSIONS

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ABSTRACT

In today's technological world, it is difficult to neglect the extensive usage of IC engines. Though diesel engines are preferred over gasoline engines because of various reasons, they produce higher emissions particularly oxides of nitrogen (NO_x) and soot. Attempts are made to design an engine with better efficiency and minimum emissions by modifying the existing engine technologies and developing better after treatment systems. Since after-treatment systems are costly and occupy more space, in-cylinder solutions like exhaust gas recirculation (EGR), variable compression ratio, air intake improvements, and fuel injection characteristics are preferred. CONVERGE, a computational fluid dynamics (CFD) tool, is used for this analysis. Adaptive Mesh Refinement (AMR), parallelization and other powerful capabilities of CONVERGE have made it most suitable for engine studies. Numerical pressure curve has been validated against the generated experimental data. A very good comparability has been observed for the pressure curve over a wide range of crank angle. Based on good validation, Converge tool is used to study the effects of EGR on diesel engine emissions. The results indicate that the use of EGR leads to a decrease in peak pressure, which in turn reduces NO_x . At the same time, there is an increase in soot amount. HC and CO emissions were also increased with increasing amount of EGR. The presence of CO_2 and H_2O in EGR increase the delay and reduce the reaction rate.

Keywords: CONVERGE, Compression Ignition engine, Exhaust Gas Recirculation, Emissions

1. INTRODUCTION

Presently, there are over one billion automobile users, which run on internal combustion (IC) engines. IC engines are used because of their excellent power to weight ratio. Diesel engines are preferred over gasoline engines because of better fuel economy, better part load efficiency, more reliability and higher torque output [1]. However, diesel engine produces higher emissions particularly oxides of nitrogen (NO_x) and soot. The proportion of these gases in the atmosphere is increasing and has to be maintained;

else it may have hazardous impact on environment and human beings. The main focus of research is to minimize the release of these gases into atmosphere by using efficient technology. Hence attempts are made to design an engine with better efficiency, low fuel consumption and minimum emissions which can be obtained by modifying the existing engine technologies and developing better after treatment systems [2]. Since after-treatment systems are costly and occupy more space, in-cylinder solutions such as exhaust gas recirculation, variable compression ratio, air intake improvements, and fuel injection characteristics are preferred in reducing emissions [3]. A detail study of in-cylinder solutions has been discussed by Brijesh and Sreedhara [3] in their review paper. Exhaust gas recirculation, a method which re-circulate a portion of engine exhaust air into the combustion chamber through inlet system, is proven to be an effective technique to reduce NO_x emissions. Murata et al. [4] had also proposed the results which indicated the reduction in NO_x and soot emissions at constant EGR. Ehleskog et al. [5] had analyzed the effects of charge air pressure and EGR on combustion and emissions of a single cylinder diesel engine. Results showed insignificant effects on soot emissions but produced higher NO_x without EGR. However higher charge pressure along with EGR resulted in higher NO_x . On the contrary, higher NO_x and lower soot emissions were observed by Jayashankara et al. [6] in their numerical study, with higher charge pressure and without EGR.

Thus the reduction of emissions from IC engines has become a main focus area of research to meet stringent emission regulations. In this direction, numerical work has been done to validate the experimental data and to study the effect of EGR. Effect of EGR with varying percentages on emissions in diesel engine has been analyzed. CONVERGE, a CFD tool, has been used for simulation. Similar work using CONVERGE has been carried out by Harshvardhan and Sreedhara [7] to study the effect of number of injector holes, spray angle, spray cone angle and injection duration on diesel engine performance and emissions. It is very useful in simulating IC engine problems, advanced turbulence, performance characteristics, and spray and combustion models with moving mesh capabilities [8, 9]. Based on literature study, effect of EGR on diesel engine emissions has been studied in this work by using Converge.

2. EXPERIMENTAL SETUP

The test rig consists of a single cylinder, four strokes, direct injection (DI) diesel engine connected with an eddy current type dynamometer. Necessary instruments such as in-cylinder and fuel line pressure transducer, crank angle encoder etc. are mounted to obtain $p-\theta$ diagram providing vital information regarding engine performance. Other instruments for measuring air flow rate, fuel flow rate, temperature at various locations and load are also integrated into the test rig. A schematic of the experimental setup is shown in Fig. 1. Specifications of engine are given in Table 1.

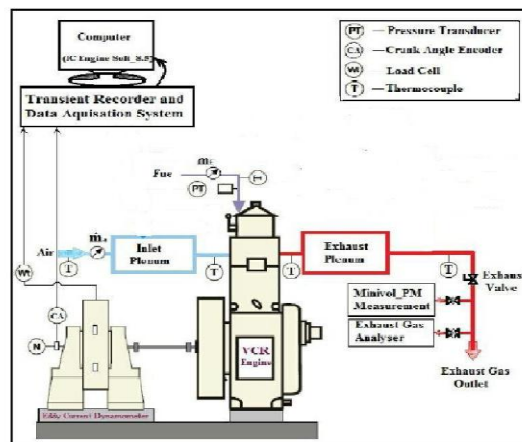


FIGURE 1. SCHEMATIC OF EXPERIMENTAL TEST RIG

TABLE 1. ENGINE SPECIFICATIONS

Compression Ratio	18
Cylinder bore x stroke	87.5mm □ 110mm
Piston bowl shape	Hemisphere
Piston bowl diameter	52mm
Fuel injection pressure	220 bar
Fuel injection timing	□ 27 CAD aTDC
Number of nozzle holes	3
Nozzle hole diameter	0.288mm
Connecting rod length	234 mm
Inlet valve closes	□ 145 CAD aTDC
Exhaust valve opens	145 CAD aTDC

Experimental run was carried out at 75% load (9 kgf) and 1500 rpm. Pressure curve produced with the help of experiment has been used for validation purpose.

3. NUMERICAL INVESTIGATION

3.1 Converge tool

CONVERGE is a Computational Fluid Dynamics tool for the simulation of three-dimensional, incompressible/compressible, chemically reacting transient fluid flows in complex geometries with stationary or moving surfaces. CONVERGE can handle an arbitrary number of species and chemical reactions, as well as transient liquid sprays, and laminar or turbulent flows. CONVERGE uses an innovative boundary approach that eliminates the need for the computational grid to coincide with the geometry of interest. The adaptive mesh refinement (AMR) technique in CONVERGE enables local mesh refinement according to temperature, velocity and species gradients [10]. Refinement of the mesh as the combustion in a chamber proceeds can be seen clearly from Fig. 2.

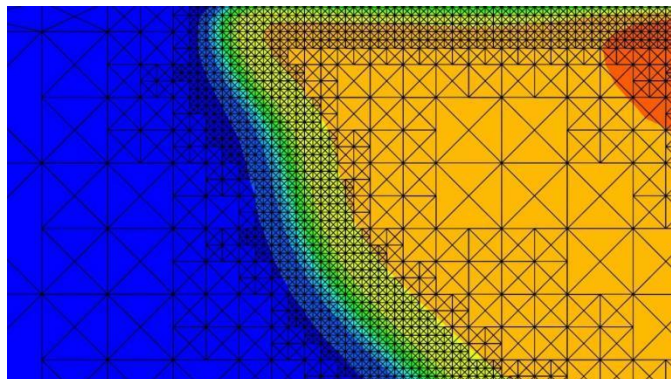


FIGURE 2. ADAPTIVE MESH REFINEMENT NEAR HIGH TEMPERATURE GRADIENTS

The base grid resolution is specified in an input file, thus allowing for grid resolution studies to be performed without making separate meshes. The geometry volume is always correctly calculated, allowing for extremely coarse meshes to be used while setting up a case. For more information, see Ref.

[11]

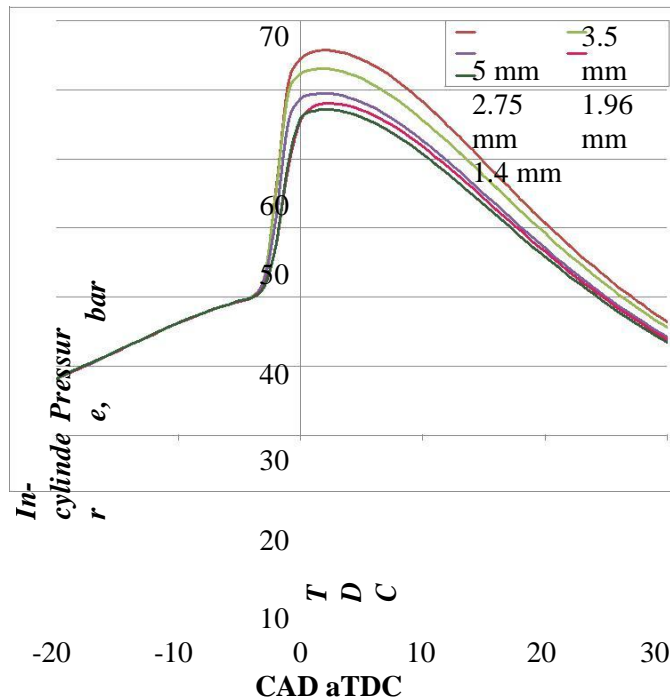
For simulation purpose diesel fuel has been substituted with an equivalent fuel C_7H_{16} . A variant of $k-\varepsilon$ ring turbulence model by taking usual constants $c_1=1.42$ and $c_2=1.68$. The KH-RT breakup model along with NTC collision model has been employed. Injection profile shape is given as an input. Using the input values of injection duration and mass of fuel injected, CONVERGE tool scales the given injection profile to inject the given mass of fuel in the given duration. Ignition has been modeled using a multistep kinetics model based on Shell model [12], while the characteristics time model has been used to model combustion [13]. For this case, the extended Zeldovich

NO_x model [14] and the Hiroyasu soot model [15] have been used for exhaust emissions.

The converge tool played an important role in numerical investigation of the experimental results, when the engine specifications data was fed in.

3.2 Grid independence study

The approach of CONVERGE which eliminates the need for computational grid to coincide with geometry of interest has advantages as discussed earlier. Thus it is essential to make the data grid independence. The numerical result obtained was fine-tuned with respect to the grid size in order to find the optimum of it. Variation in pressure of the cylinder was studied as the grid size was changed. Starting from 5 mm, grid size was progressively reduced till no further significant variation in pressure curve was observed. Figure 3 shows the pressure curves for different grid sizes. It can be seen from the Fig. 3, that the curves differ with each other significantly for grid size of 5 mm to 2.75 mm, but the curves for grid size 1.96 mm and 1.4mm almost coincide with each other. Hence, base grid size taken for all simulation purposes in this work was considered at 1.96 mm.



FIGU E 3. EFFECT OF GRID SIZE ON IN-CYLINDER PRESSURE

3.3 Code validation

Code has been validated against the results of experimental engine stated above. As mentioned in Table 1, engine is having 3 nozzles, so 120° sector model was used for validation. Sector is chosen such that it can house one injector nozzle at its centre. Numerical run was carried out from the inlet valve closing (IVC) i.e. -145 CAD aTDC to the opening of exhaust valve i.e. 145 CAD aTDC. Figure 4 shows the comparison of experimental and numerical pressure traces as a function of crank angle. For simulating the experimental results, minor modifications are made for conditions at IVC and model constants so that the pressure trace match well with the experimental data. As shown in Fig. 4, very good comparability has been observed for the pressure over a wide range of crank angle. Converge slightly under predict at the point of start of injection, hence some deviation in graph has been observed at -5 CAD aTDC. However, it may be concluded that the code has been validated well with the experimental pressure curve. Validated code has been used to study the effect of EGR on CI engine emissions. Hence, Converge runs have been carried out with 10% and 20% EGR by keeping remaining parameters as it is.

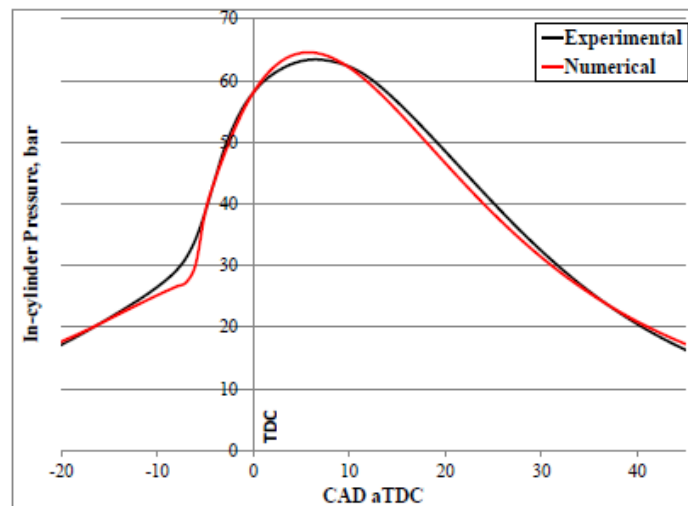


FIGURE 4. COMPARISON OF EXPERIMENTAL AND NUMERICAL PRESSURE TRACES

4. RESULTS AND DISCUSSIONS

Effect of EGR on in-cylinder pressure, NO_x, soot, HC and CO has been investigated. The percentage of EGR has been calculated on mass basis by using following

formula:

$$\% \text{ EGR} = \frac{\text{Mass of EGR}}{\text{Mass of EGR} + \text{Mass of intake air}} \times 100$$

Results are discussed in details as below.

4.1 Effect of EGR on in-cylinder pressure

Variations of in-cylinder pressure as a function of crank angle, with various EGR percentages are plotted in Fig. 5. It is observed that the in-cylinder pressure curve is altered extensively with increasing EGR. In-

cylinder pressure traces of the runs with 10% and 20% EGR are shifted towards the expansion stroke. Lower peak pressure was also observed with increased EGR. EGR mainly contains carbon dioxide (CO₂) and water vapour, which absorbs more heat during compression and combustion. As a result, lower peak pressure and hence lower in-cylinder temperature was observed with increasing amount of EGR. It can be concluded that dilution effect of EGR slow down the reaction rate. The percentage decrease in peak pressure with 10% EGR is 4.76% and with 20% EGR is 14.2%

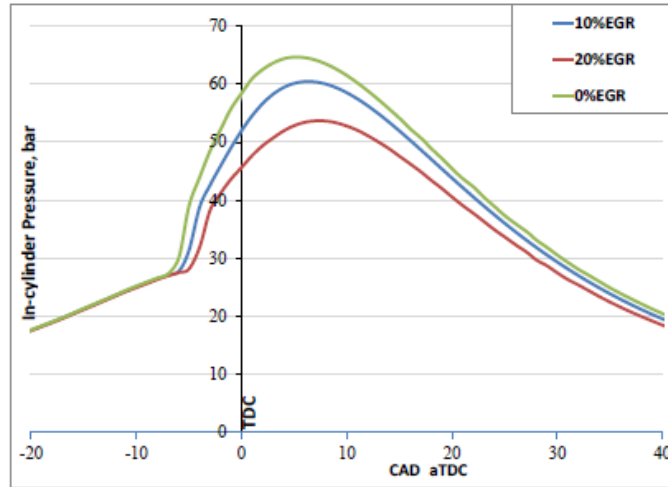


FIGURE 5. EFFECT OF EGR ON IN-CYLINDER PRESSURE

4.2 Effect of EGR on NO_x and soot

Figure 6 shows the values of NO_x and soot with varying percentage of EGR. The amount of NO_x, as shown in Fig. 6, decreases with an increase in EGR. Significant production of nitrogen oxides is due to the lean-burning nature of diesel engines and the high temperatures and pressures of the combustion process. EGR acts as diluent to the combusting mixture and reduces the O₂ concentration in the combustion chamber. The specific heat of the EGR is much higher than fresh air, hence EGR also increases the heat capacity of the intake charge, thus decreasing the temperature rise for the same heat release in the combustion chamber. Hence a decrease in NO_x, as shown in Fig. 6, is observed with increase in EGR percentage. On the other hand, lower combustion temperature with EGR leads to partial combustion, hence produced higher soot. NO_x is reduced by ~72% and ~74% with 10% and 20% EGR respectively. However, around 40% and 67% increase in soot is observed with 10% and 20% EGR.

4.3 Effect of EGR on HC and CO

Variations in hydrocarbons (HC) and carbon monoxide (CO) with different EGR percentage are plotted in the Fig 7. It is observed that CO and HC increase with increased EGR. This can be traced to the depletion in oxygen and lower combustion temperature with presence of EGR. Since complete combustion of carbon does not take place, higher CO is produced. Similarly, the lower combustion temperatures caused by EGR leads to higher HC emissions.

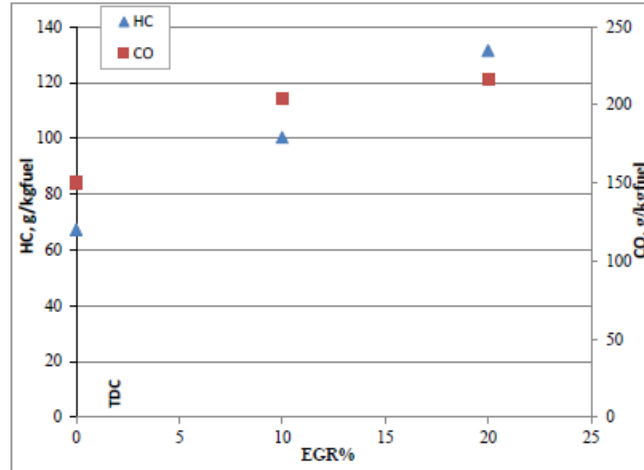


FIGURE 7. EFFECT OF EGR ON CO AND HC

5. CONCLUSION

In this paper, numerical simulations have been carried out using the CONVERGE CFD-tool to evaluate the effects of EGR on emissions. CONVERGE tool has been validated against the published experimental data for pressure trace. This detailed study revealed that EGR is an effective method for reduction of NO_x emissions, which are comparatively much hazardous than the other exhaust gases. NO_x emissions have a negative impact on engine performance since it decreases peak pressure which directly affects the efficiency and increases the fuel consumption. Also there is an increase in soot, HC and CO emissions. But these emissions, being small, can be controlled.

CONVERGE can also be used to investigate the engine performance by varying the various engine parameters. Future work includes the numerical investigation of engine performance by changing compression ratio (CR), number of injectors, bowl profile and nozzle angle.

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