Investigation on Combustion analysis and simulations of HCCI Engine on performance and emissions

[1]P.V.Ramana, [2]D.Maheswar, [3]B.Durgaprasad

[1]Associate professor (Research Scholar JNTUA), [2]professor, [3]professor&HOD
[1]Mechanical Engineering Department-CVR college of Engineering-Hyderabad (T.S)-India,
[2]Principal- Keshav Memorial Institute of Technology-Narayanaguda-Hyderabad (T.S) - India,
[3]Mechanical Engineering Department-JNTUA college of Engineering –Anantapur(A.P)-India

***Abstract*— Diesel engine combustion analysis for performances like brake thermal efficiency, specific fuel consumption, volumetric analysis and emissions like NOx, CO,CO_2HC is complex phenomenon which is influenced by number of parameters like fuel injection system, fuel properties and operating parameters of the engine. So it is difficult to study the characteristics of combustion and heat transfer inside the combustion chamber. It is the most challenge area to study the combustion and conducting experimental investigation of flow of combustion unless advanced combustion techniques are used. It can be studied with advanced techniques by establishing correlations between experimental parameters of performance and emissions with CFD analysis. The CFD analysis used for performance and emissions of HCCI mode of Engine operation at different load conditions with different EGR flow rates. The obtained results are simulated and experimental combustion mode validated in this present study.**

***Index Terms*—CI, CFD, HCCI, EGR, FLUENT**

1.0 INTRODUCTION

There is extremely complex combustion process in I.C. engines. Computer aided modeling & simulation techniques can be used to perform dynamic analysis of a complex combustion system. The computer generated model is analyzed using C language. There are certain assumptions in this combustion as follows

- Combustion chamber is divided in to burned and unburned region
- The burned region is divided further and segregated as mixed region
- In mixed region air fuel is mixed which is ready for chemical reaction
- In non premixed combustion region fuel and air are in segregated region
- Finally in the burned region is the mixed reactant into the mixed region for combustion.

2.0 OBJECTIVES OF THE ANALYSIS

- To evaluate the performance and emission of diesel fuel on CI and HCCI mode of operation under different operating conditions with and without EGR
- To make a comparative analysis of the engine performance and emissions (pollution aspects) with diesel fuel operation.
- To study the effect of variation of EGR on the performance and emissions of the engine running with diesel on CI and HCCI mode of operation.
- To develop simulation code for CI and HCCI diesel fuel in the diesel engine.
- To compare results obtained through simulation with the experimental results.
- To develop CFD analysis for combustion of HCCI mode of operation of CI engine with diesel fuel.

3.0PHYSICAL DOMAIN

After several modifications for the true model of the combustion chamber on GAMBIT, a more appropriate model for analysis on FLUENT is obtained. In the final model the thickness of the combustion chamber, cylinder head and the piston is reduced to 3 mm without altering the diameter of the combustion chamber and other critical dimensions. This modification reduces the number of nodes and elements created while meshing the model. This saved considerable amount of time and computing resources for iterations on FLUENT.

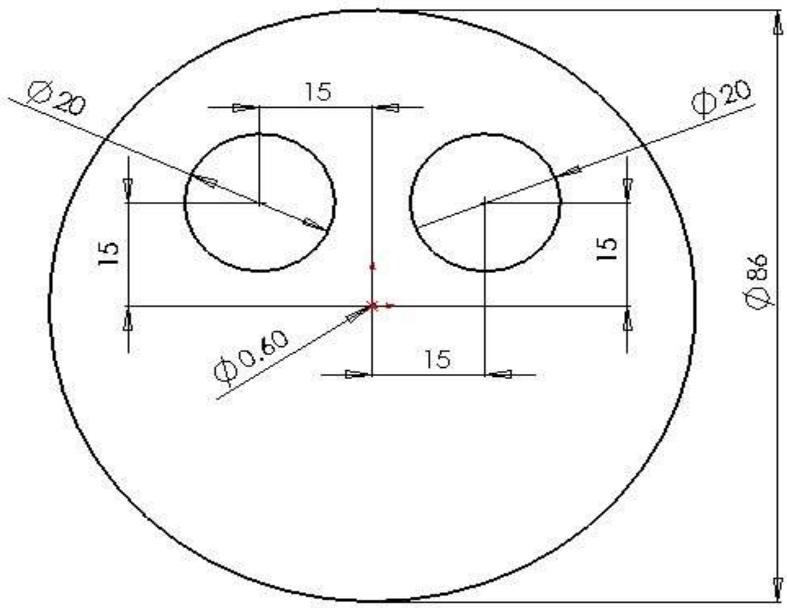


Figure1.Positioning of Nozzle and Valves on Cylinder head

Bore diameter = 80 mm (Not shown in the figure)

Nozzle Diameter = 0.6 mm

Valve diameter = 20 mm

Outer diameter of cylinder = 86 mm (Modified for simplicity)

The mesh used for this model is Hex/Hybrid (Cooper). This mesh type is apt for such geometry and enables easy importing of the model into FLUENT.

The model is a virtual prototype of the combustion chamber at the end of compression stroke. Diameter and Height are a prerequisite for creating the cylindrical combustion chamber. Diameter of the chamber is known, which is equal to bore diameter (80 mm). The height H (i.e. distance between the piston top and cylinder head at the end of compression stroke), is calculated as shown below:

$V_{displacement} = \Pi/4 * d^2 * L$

d = Bore diameter (80 mm)

L = Stroke length (110 mm)

$V_{displacement} = \Pi/4 * 80^2 * 110$

$V_{displacement} = 552920.307\ mm^3$

$V_{clearance} = [V_{displacement} / (r - 1)]$

r = Compression ratio

For r = 16.5; $V_{clearance} = 35672.27\ mm^3$

$\Pi/4 * 80^2 * H = 35672.27$

The value of height H is obtained as 7.0967 mm from the above equation.

3.1 Computational Fluid Dynamics

Computational Fluid Dynamics is a computational technology that helps to study the dynamics of fluids that flow. Using computational fluid dynamics we can build a model that represents a system which we want to study. By apply the fluid flow physics and chemistry to this virtual prototype, the software will generate a prediction of the fluid dynamics. CFD is a sophisticated mathematically based design and analysis technique. The commercial codes such as FLUENT, VECTIS and STARD are commonly used in automobile engineering.

3.2 Pressure Outlet Boundary Conditions

Pressure outlet boundary conditions require the specification of a static (gauge) pressure at the outlet boundary. The value of static pressure specified is used only while the flow is subsonic. If the flow becomes locally supersonic, the specified pressure is no longer used.

A set of "backflow" conditions are also specified to be used if the flow reverses direction at the pressure outlet boundary during the solution process. Convergence difficulties will be minimized if one specifies realistic values for the backflow quantities. This is applied at the outlet for gases.

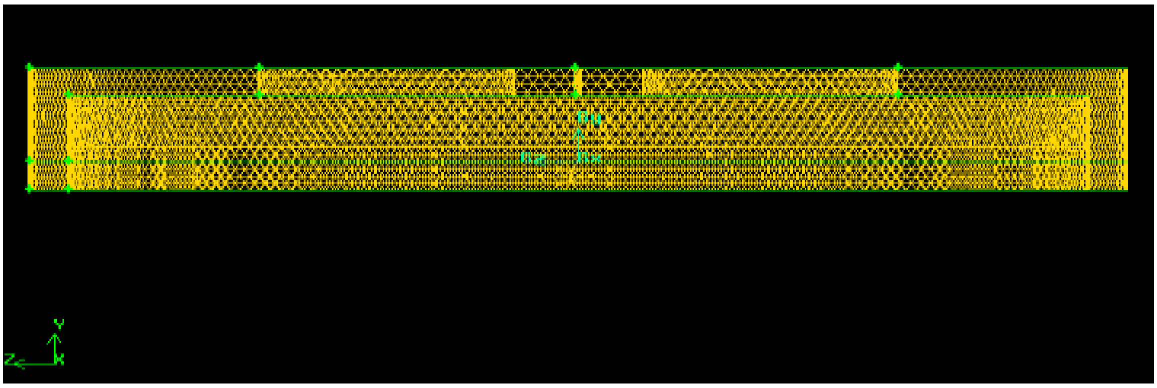


Figure2. Mesh Model

3.3 Modeling Capabilities of the FLUENT solver

- The flow in two dimensional or three dimensional geometries using unstructured solution adaptive triangular/tetrahedral/quadrilateral hexahedral or mixed grids that include prisms or pyramids.
- The incompressible / compressible flows in fluid dynamics.
- The steady state / transient analysis.
- The laminar and turbulent flows.
- The Newtonian /non-Newtonian flows.
- The convective H.T. including natural / forced convection.
- The radiation heat transfer.
- The phase change models.
- The flow through porous media.
- The multi-phase flows, including cavitations.

These features allow FLUENT to be used for a wide variety of applications, including the following listed below:

- The power generation and oil or gas and environmental applications.
- The aerospace applications and turbo machinery
- The heat exchanger applications.
- The electronics/HVAC/appliances.
- The materials processing applications.
- The architectural designs and fire research.

3.4 Combustion Modelling

- Computer code has been developed by using high level C language by taking into consideration ideal cycle, adiabatic cycle and actual cycle.
- Combustion analysis is done using CFD code, combustion in the cylinder is modeled in the GAMBIT and the mesh is improved to FLUENT for the analysis.
- Experimentation is carried out for biogas - diesel dual fuel in the compression ignition engine.
- Results are compared.

3.5 Assumptions of Simulation

- Working medium is assumed to be air-fuel mixture with variable specific heats.
- Combustion takes place adiabatically at constant pressure.
- Heat transfer process is not considered.
- Exhaust and intake process is considered.
- The operation is naturally aspirated.

3.6 Computational Method

The basic steps are:

- To create the model geometry and grid
- To start the appropriate solver for 3D modeling
- To import the grid
- To check the grid
- To select the solver formulation
- To chose the basic equation to be solved: laminar / turbulent/ chemical reactions/ heat transfer analysis etc.
- To specify material properties
- To specify the boundary conditions
- To adjust the solution control parameters
- To initialize the flow field
- To calculate the solution
- To examine the results
- To save the results

3.7 Governing Equations

- Analysis on FLUENT is being carried out using segregated, three dimensional solver. The model of species transport is used for defining the reacting species. The k-ε model is used as turbulence analysis model.

$$\rho\frac{Dk}{Dt} = \frac{\partial}{\partial xi}\left[\left(\mu+\frac{\mu t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right] + G_K + G_b - \rho\varepsilon - Y_M$$

$$\rho\frac{D\varepsilon}{Dt} = \frac{\partial}{\partial xi}\left[\left(\mu+\frac{\mu t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_i}\right] + C_{l\varepsilon}\frac{\varepsilon}{K}\left(Gk + G_{3\varepsilon}G_b\right) - C_2\rho\frac{\varepsilon^2}{K}$$

3.8 Boundary Conditions

Boundary conditions specify the flow and thermal variables on n the boundaries of a physical model. They are, therefore, a critical component of FLUENT simulations and it is important that they are specified appropriately.

3.9 Available Boundary Types

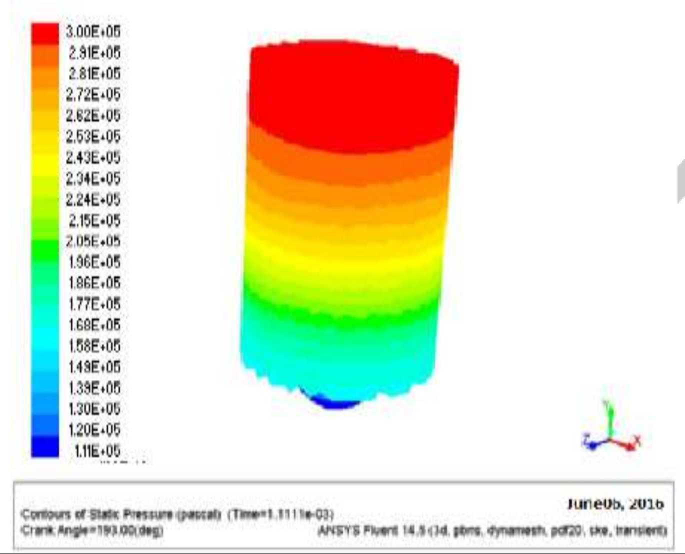
The boundary = $\boldsymbol{\beta}_{gi}\frac{\mu_t}{Pr_t}\frac{\partial T}{\partial x_i}$ types available in FLUENT are classified as follows:

- Flow inlet and exit boundaries: pressure inlet, velocity inlet, mass flow inlet
- vent, intake fan, pressure outlet, outflow, outlet vent, exhaust fan
- Internal cell zones: fluid, solid (porous is a type of fluid zone)
- Internal face boundaries: fan, radiator, porous jump, wall, interior

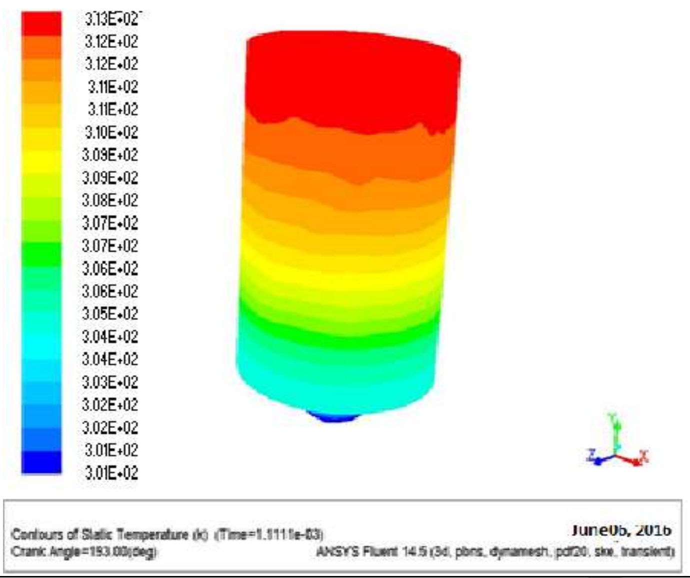
4.0 Simulation Contours

The following contours are obtained as results of simulation;

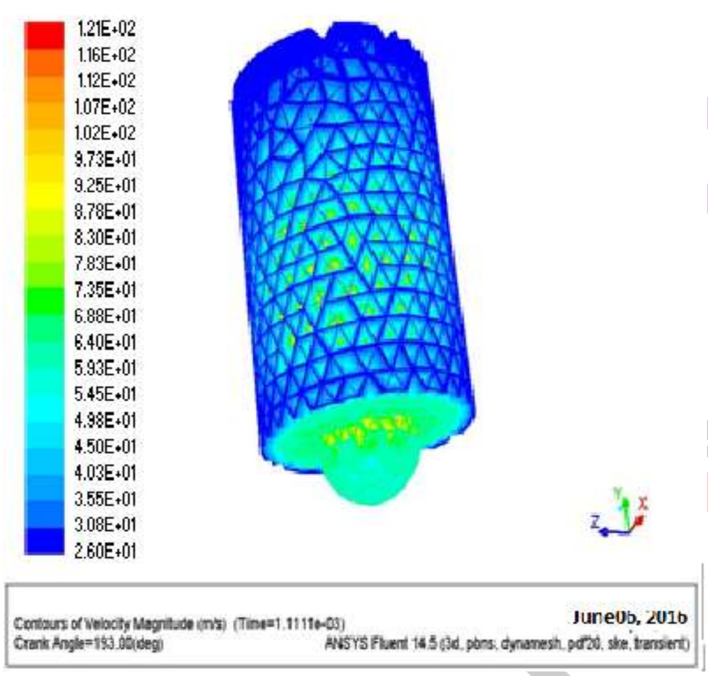
- The contours illustrate the conditions of pressure,
- temperature,
- Kinematic viscosity etc., at each node of the mesh.



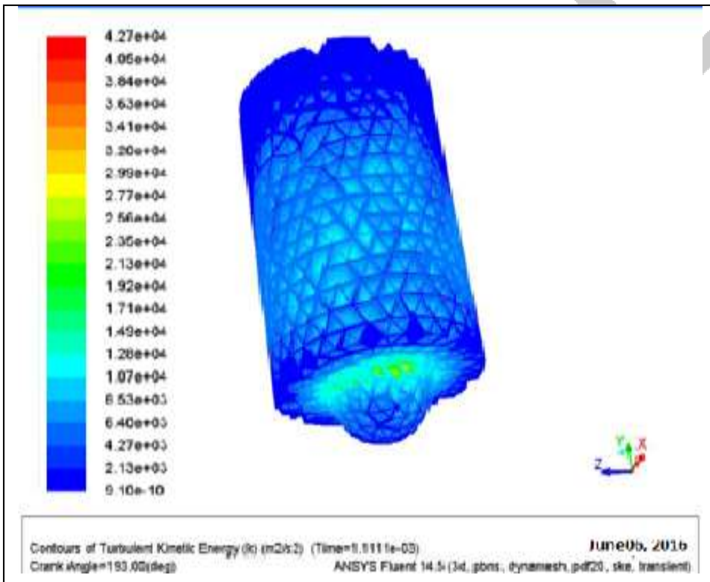
The simulated result of the adjacent box at normal CI conditions shows variation of static pressure at various zones in the cylinder at 193 CA deg.



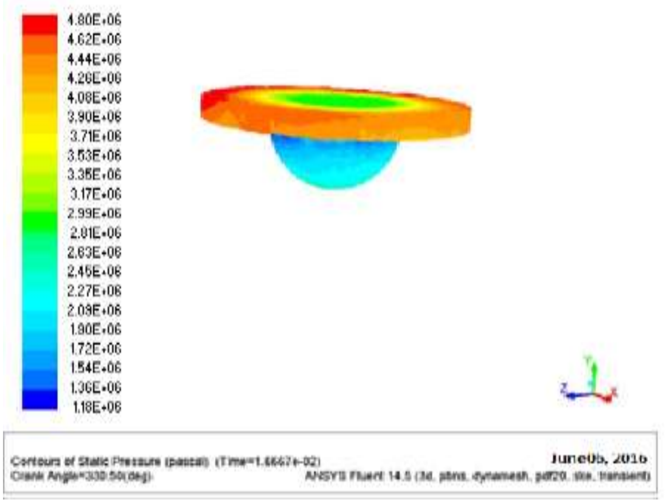
The simulated result of the adjacent box at HCCI conditions shows variation of static temperature at various zones in the cylinder at 193 CA deg.



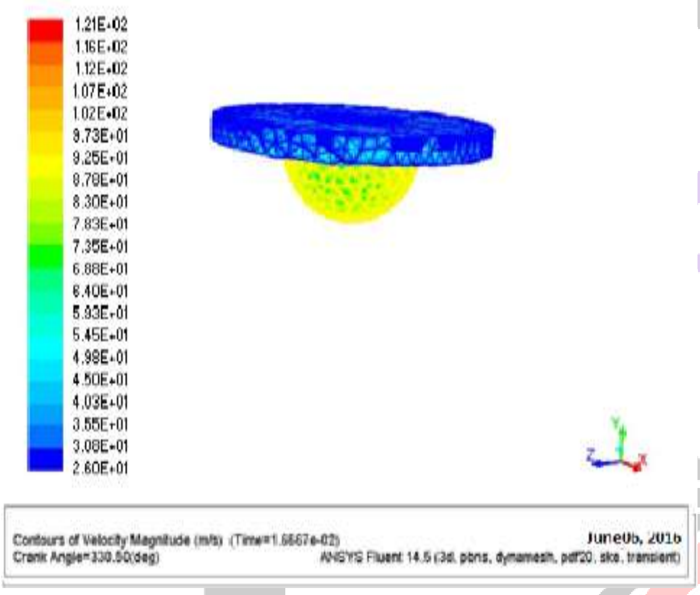
The simulated result of the adjacent box at normal CI conditions shows variation of velocity magnitude at various zones in the cylinder at 193 CA deg. .



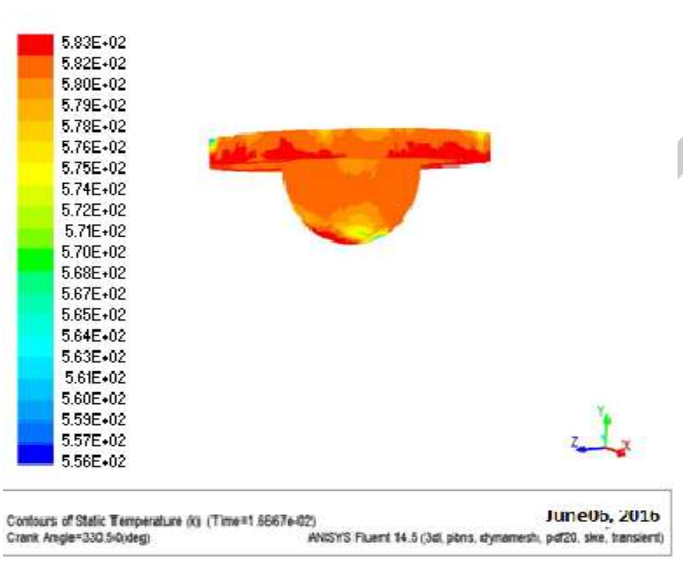
The simulated result of the adjacent box at HCCI shows variation of Turbulent Kinetic Energy at various zones in the cylinder at 193 CA deg.



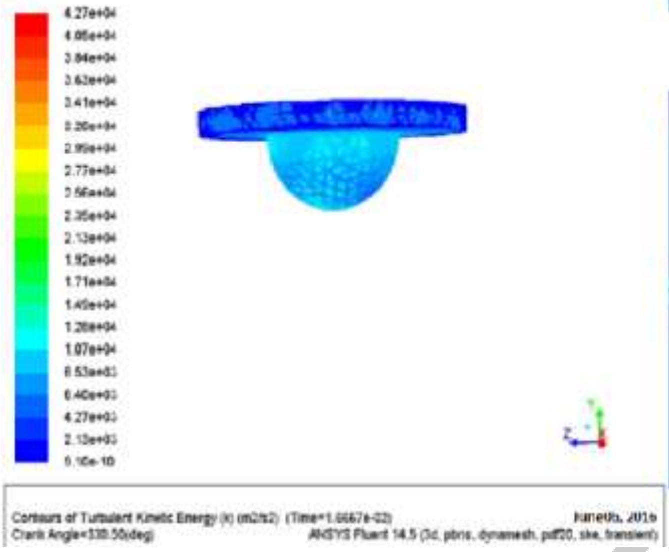
The simulated result of the adjacent box at HCCI shows variation of static pressure at various zones in the cylinder at 330.5 CA deg.



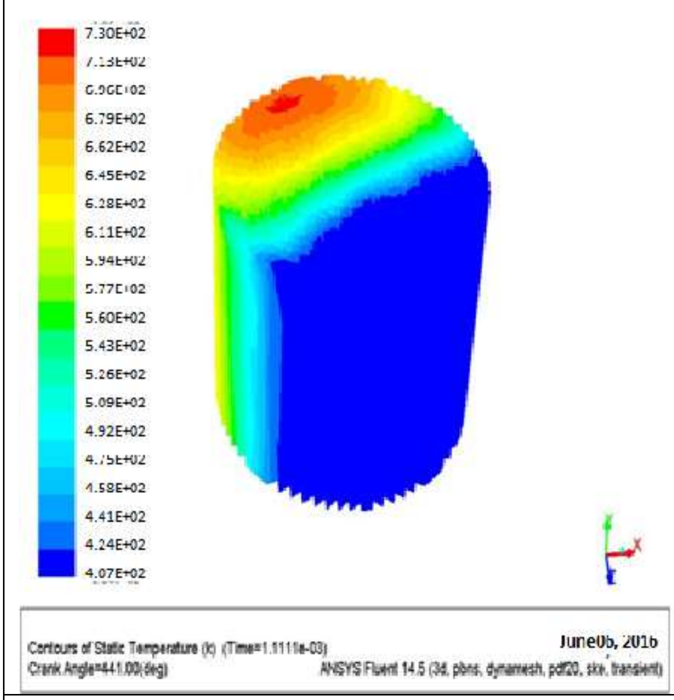
The simulated result of the adjacent box at normal CI conditions shows variation of velocity magnitude at various zones in the cylinder at 330.5 CA deg. .



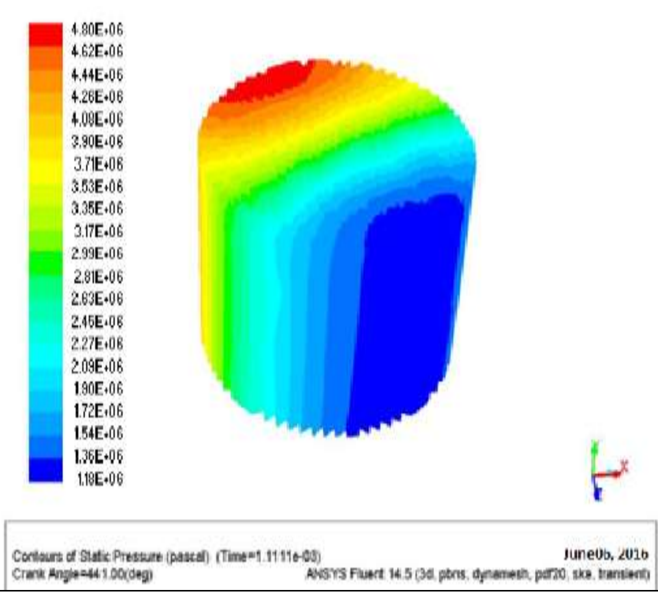
The simulated result of the adjacent box at HCCI conditions shows variation of static temperature at various zones in the cylinder at 330.5 CA deg.



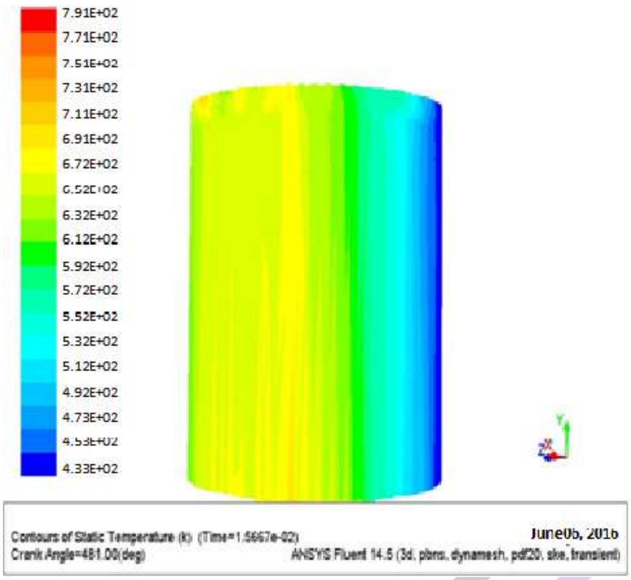
The simulated result of the adjacent box at normal CI running conditions shows variation of turbulent kinetic energy at various zones in the cylinder at 330.5 CA deg. .



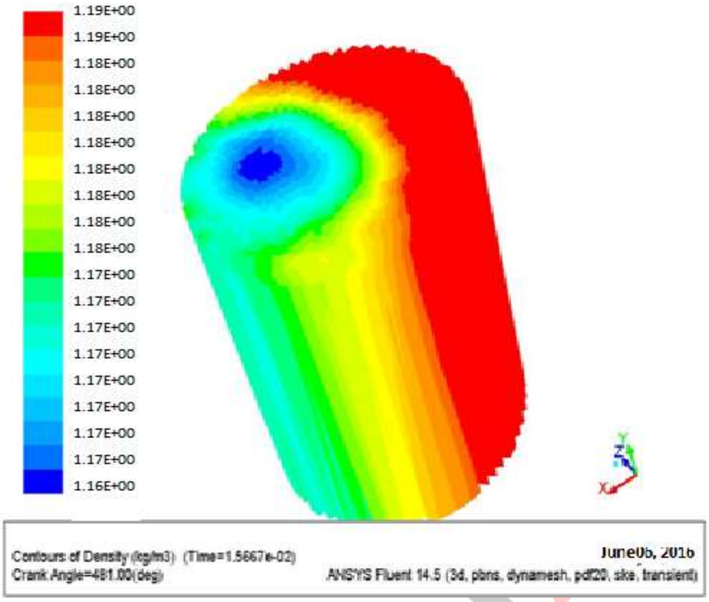
The simulated result of the adjacent box at Normal CI conditions shows variation of static temperature at various zones in the cylinder at 441 CA deg.



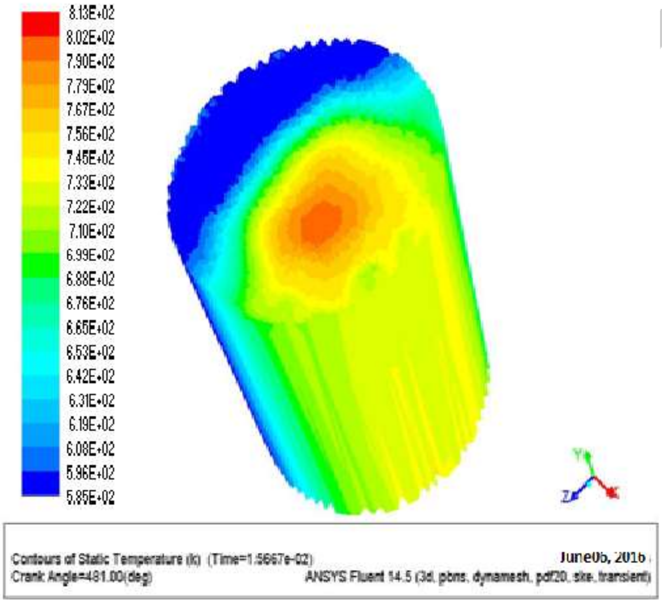
The simulated result of the adjacent box at HCCI shows variation of static pressure at various zones in the cylinder at 441 CA deg.



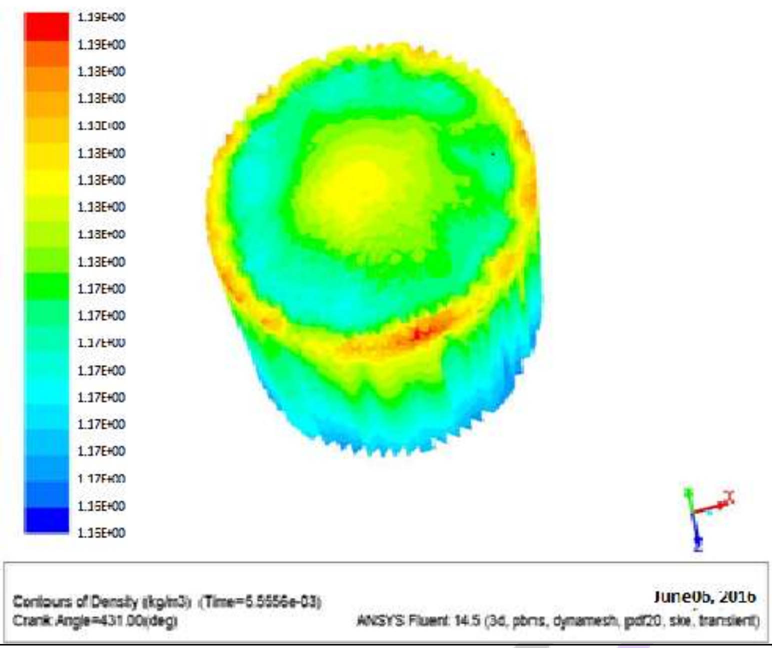
The simulated result of the adjacent box at normal CI conditions shows variation of contours of static temperature at various zones in the cylinder at 481 CA deg.



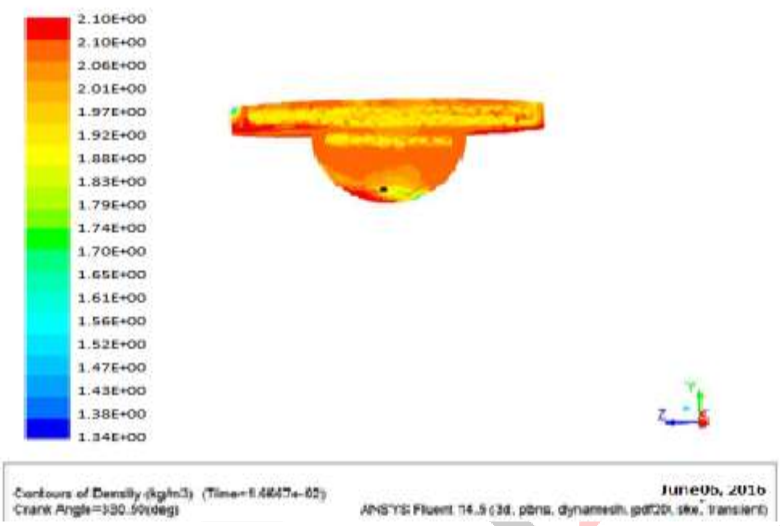
The simulated result of the adjacent box at HCCI conditions shows variation of contours of density at various zones in the cylinder at 481 CA deg.



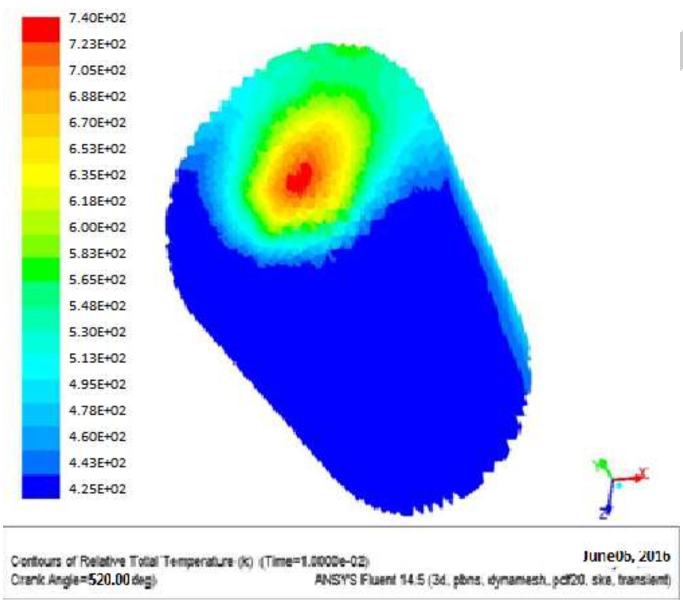
The simulated result of the adjacent box at normal CI conditions shows variation of contours of static temperature at various zones in the cylinder at 481 CA deg.



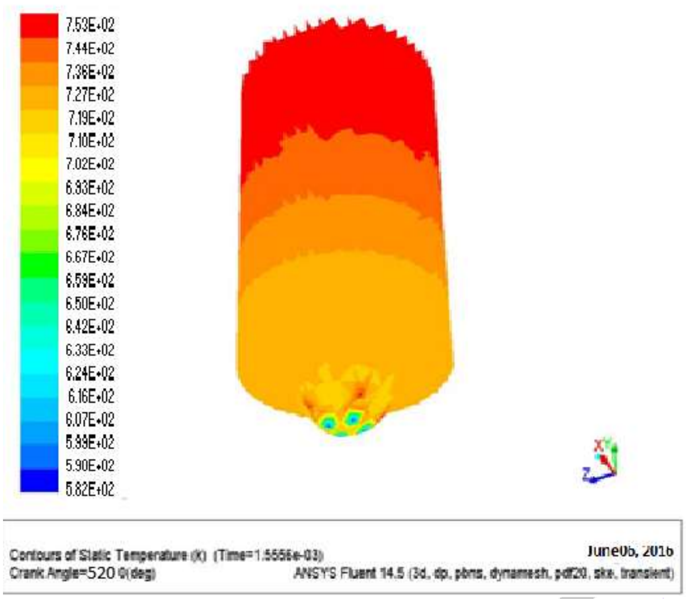
The simulated result of the adjacent box at HCCI shows variation of contours of density at various zones in the cylinder at 431 CA deg.



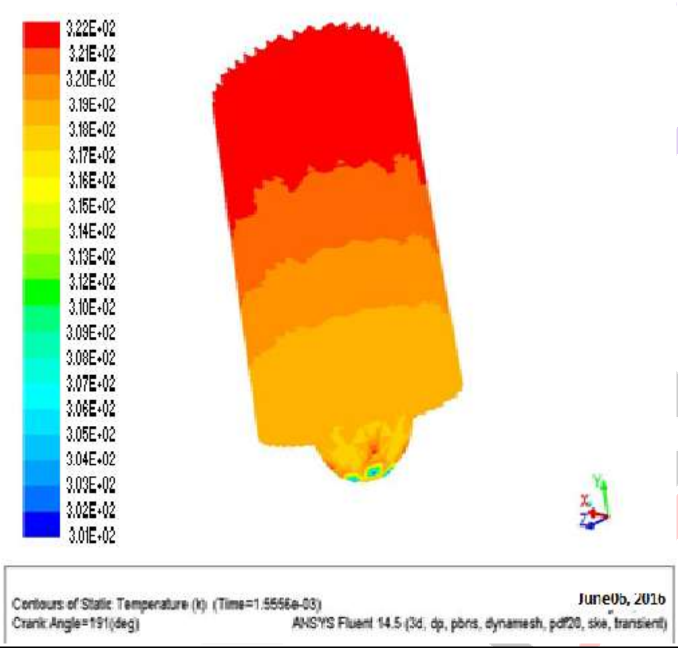
The simulated result of the adjacent box at CI conditions shows variation of contours of density at various zones in the cylinder at 330.5 CA deg. .



The simulated result of the adjacent box at normal CI conditions shows variation of contours of relative total temperature at various zones in the cylinder at 520 CA deg.



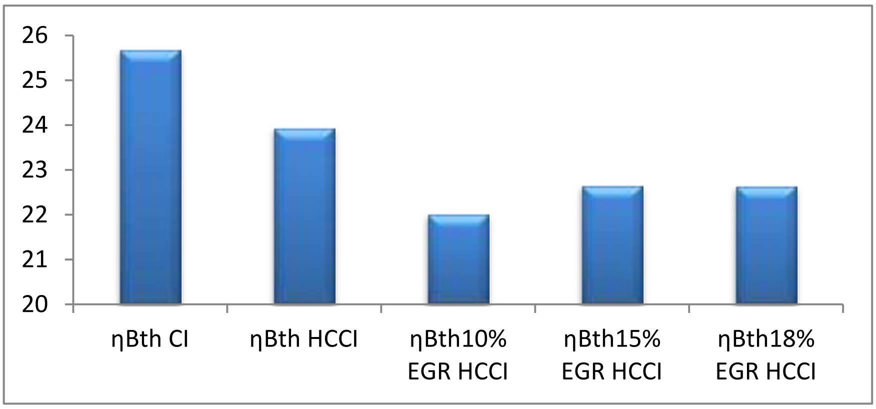
The simulated result of the adjacent box at normal CI conditions shows variation of contours of static temperature at various zones in the cylinder at 520 CA deg.



The simulated result of the adjacent box at normal HCCI conditions shows variation of contours of static temperature at various zones in the cylinder at 191 CA deg.

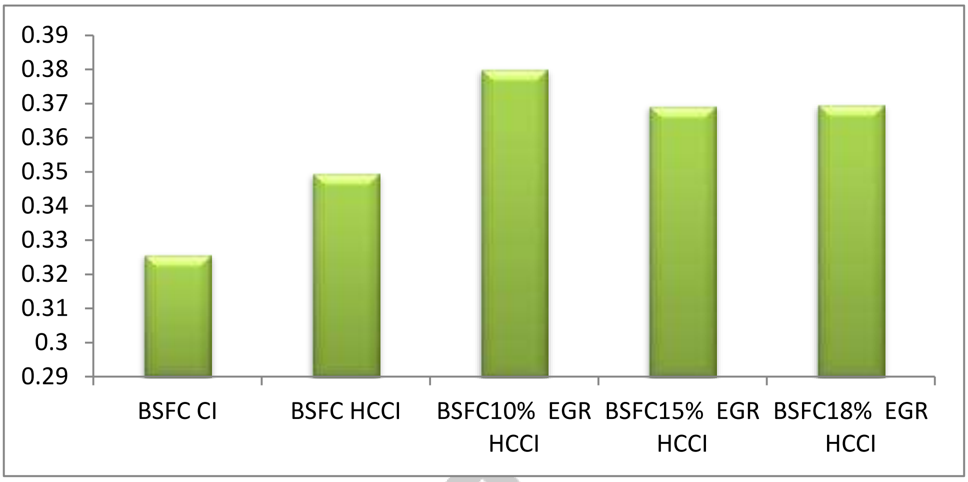
5.0 SIMULATED RESULTS OF EFFECT OF EGR ON ENGINE PERFORMANCE

5.1 Brake thermal efficiency



Graph 1: Simulated Brake thermal efficiency

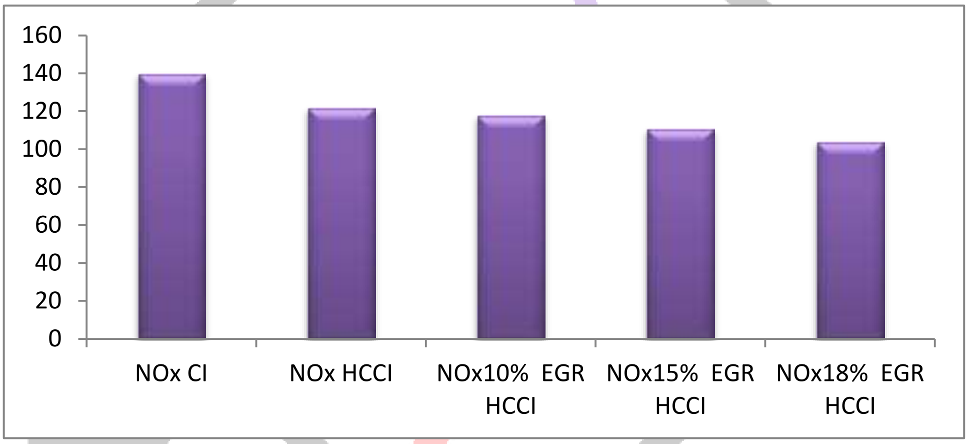
5.2 Specific fuel consumption



Graph 2 : Simulated Brake Specific Fuel Consumption

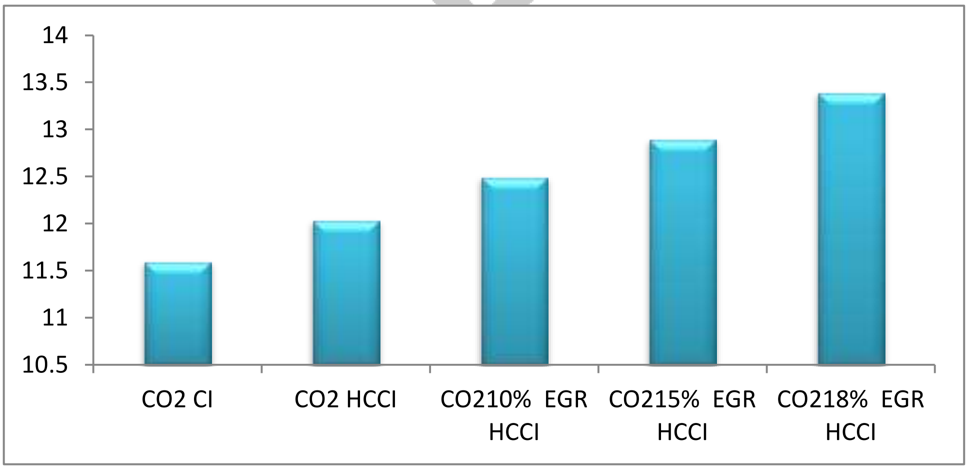
6.0 SIMULATED RESULTS OF EFFECT OF EGR ON ENGINE EMISSIONS

6.1 NOx emissions



Graph 3 : Simulated NOX Emissions

6.2 Carbon dioxide emissions

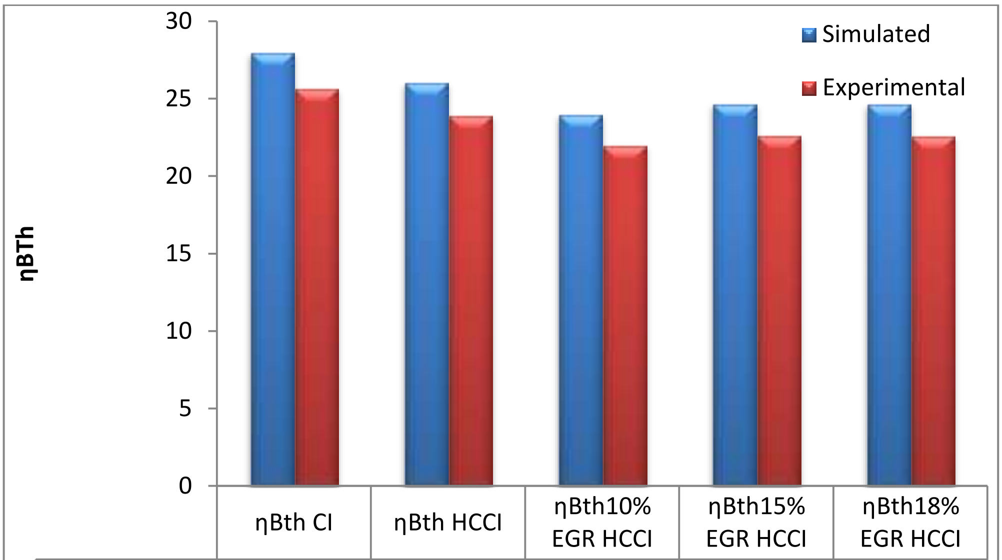


Graph 4 : Simulated Carbon di-oxide emission

7.0 VALIDATIONS OF SIMULATED RESULTS WITH EXPERIMENTAL RESULTS

The simulated results give us an idea of the trend of performance parameters and the experimental results are compared with the simulated results.

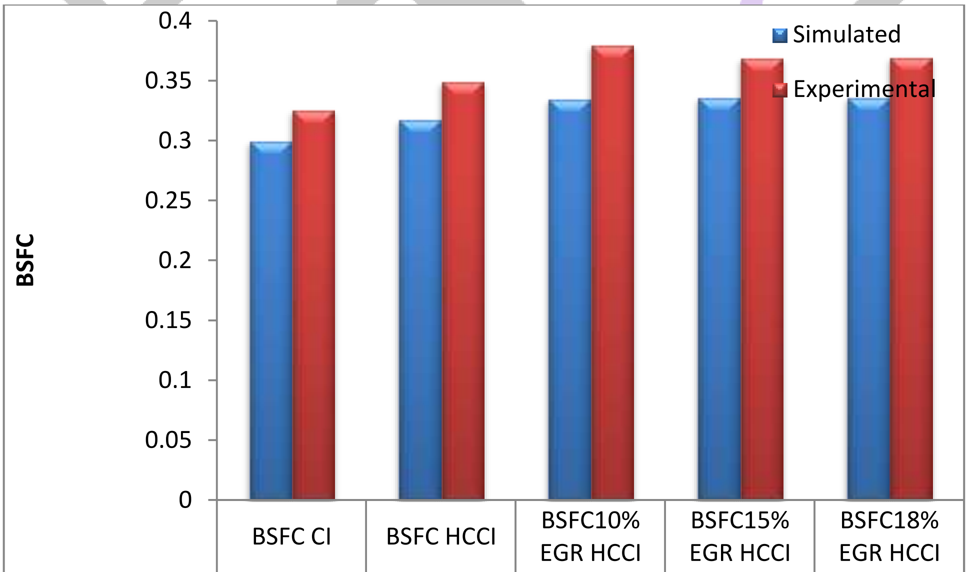
7.1 Comparison of simulated and experimental brake thermal efficiency



	ηBth CI	ηBth HCCI	ηBth10% EGR HCCI	ηBth15% EGR HCCI	ηBth18% EGR HCCI
Simulated	28.0021	26.0946	24.0018	24.6994	24.6776
Experimental	25.69	23.94	22.02	22.66	22.64

Graph5..brake thermal at CI and EGR HCCI

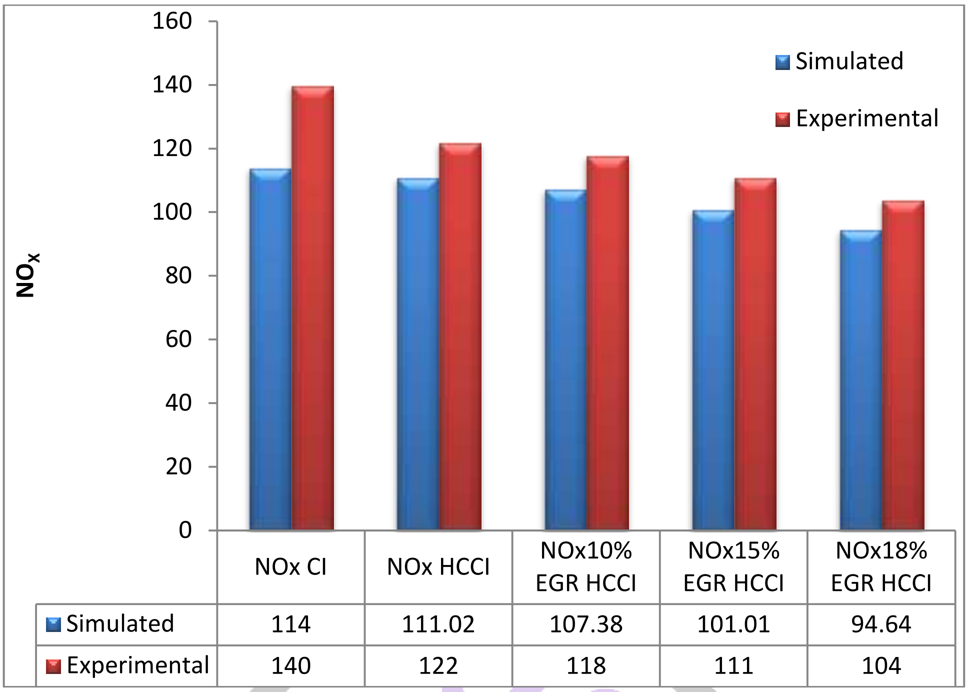
7.2 Comparison of simulated and experimental BSFC



	BSFC CI	BSFC HCCI	BSFC10% EGR HCCI	BSFC15% EGR HCCI	BSFC18% EGR HCCI
Simulated	0.3	0.318237454	0.335	0.336213798	0.336510806
Experimental	0.32588918	0.349711488	0.380204043	0.369465712	0.369792095

Graph6.BSFC at CI and EGR HCCI

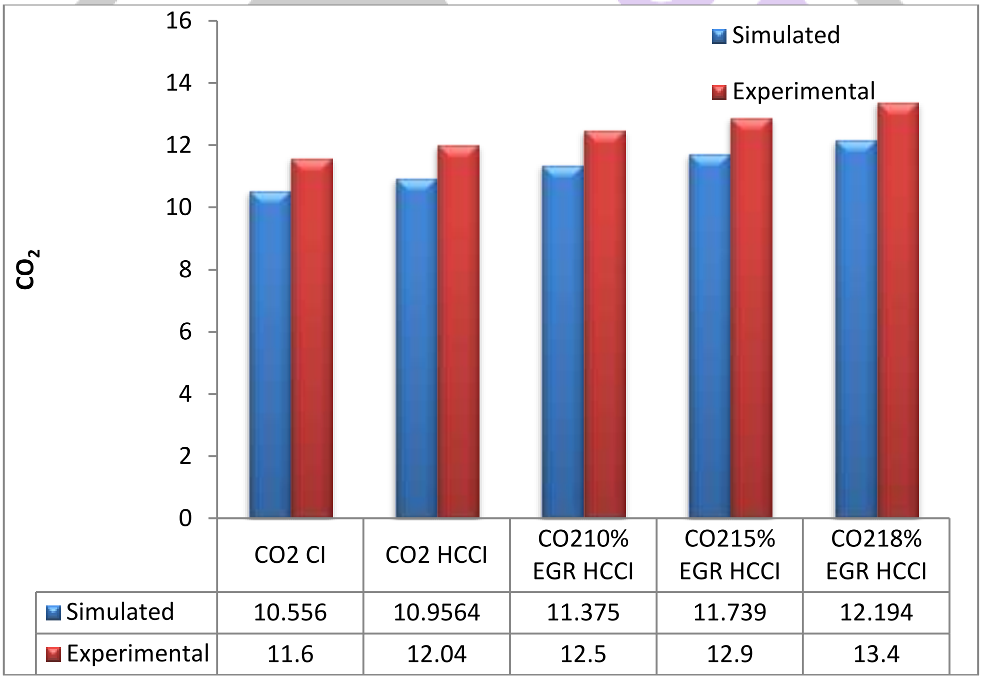
7.3 Comparison of simulated and experimental emissions of NOx



	NOx CI	NOx HCCI	NOx10% EGR HCCI	NOx15% EGR HCCI	NOx18% EGR HCCI
Simulated	114	111.02	107.38	101.01	94.64
Experimental	140	122	118	111	104

Graph7.. NOx at CI and EGR HCCI

7.4 Comparison of simulated and experimental emissions of carbon dioxide



	CO2 CI	CO2 HCCI	CO210% EGR HCCI	CO215% EGR HCCI	CO218% EGR HCCI
Simulated	10.556	10.9564	11.375	11.739	12.194
Experimental	11.6	12.04	12.5	12.9	13.4

Graph8. CO_2 at CI and EGR HCCI

8.0 CONCLUSIONS

Significant conclusions are drawn after analyzing the results obtained from the experimental and computational trails under various conditions of HCCI and EGR. The conclusions are as;

- The brake thermal efficiency of the engine is increased due to the HCCI and also due to addition of EGR till the Load is 60%. Further load application decreases the brake thermal efficiency. With EGR substitution on HCCI condition the brake thermal efficiency has increased by 12% at 18% EGR substitution at HCCI condition.
- The volumetric efficiency of the engine has decreased by HCCI and EGR substitution. The volumetric efficiency has gone down by 8 % when compared to that of normal CI conditions.
- The BSFC of the HCCI is 6% lower than the BSFC of normal CI conditions till the BP is 57%. At 71% of BP the efficiency is equal for that CI conditions. At 85% and 100% BP the efficiency is increased by 4%. the BSFC of the EGR is 4% lower by mode value than the BSFC of normal CI conditions till the BP is 57%. At 71% of BP the BSFC is equal for that CI conditions. At 85%and 100% BP the efficiency is decreased by 2%. It is inherited that the performance is going better with substitution of EGR till he load is 70%. At 18% EGR and 55% load conditions the BSFC is 21% which is 25% more than that of the normal CI conditions. At higher loads the efficiency dramatically increased from normal CI condition to 18% EGR substitution by 5%.
- The NOx emissions of the HCCI are 8% lower by median value than that of normal CI conditions. There is a drop of 9% the NOX emissions from the normal CI running conditions to 18%EGR HCCI conditions.
- The CO emissions of the HCCI are 8% lower by median value than that of normal CI conditions. HCCI enables well mixed and even combustion results in CO less burning o fuels. There is a drop of 10 % the CO emissions from the normal CI running conditions to 18% EGR HCCI conditions.
- The CO2 HCCI is 5% lower by median value than that of normal CI conditions. There is a drop of 10% the CO2 emissions from the normal CI running conditions to 18% EGR HCCI conditions.
- The HC emissions of the HCCI are 8% lower by median value than that of normal CI conditions. There is a drop of 7 % the HC emissions from the normal CI running conditions to 18% EGR HCCI conditions.
- The un-reacted Oxygen emissions of the HCCI are 6% lower by median value than that of normal CI conditions. There is a drop of 15% the O_2 emissions from the normal CI running conditions to 18% EGR HCCI conditions.

REFERENCES

[1] Chen, S., "Simultaneous Reduction of NOx and Particulate Emissions by Using Multiple Injections in a Small Diesel Engine," SAE Technical Paper 2000-01-3084, 2000, doi:10.4271/2000-01-3084.

[2] Yun H, Sun Y, Reitz R D, "An experimental and numerical investigation on the effect of post injection strategies on combustion and emissions in the low-temperature diesel combustion regime" ICES2005-1043, ASME Internal Combustion Engine Division 2005 Spring Technical Conference, Chicago IL (2005).

[3] D.T. Hountalasa, G.C. Mavropoulosa, K.B. Binderb, "Effect of exhaust gas recirculation (EGR) temperature for various EGR rates on heavy duty DI diesel engine performance and emissions", Energy, Volume 33, Issue 2, February 2008, Pages 272–283,19th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems — ECOS 2006.

[4] D.T. Hountalas, G.C. Mavropoulos, K.B. Binder, "Effect of exhaust gas recirculation (EGR) temperature for various EGR rates on heavy duty DI diesel engine performance and emissions", Energy 33 pp 272–283, 2008.

[5] B. Jayashankara, V. Ganesan, "Effect of fuel injection timing and intake pressure on the performance of a DI diesel engine – A parametric study using CFD", Energy Conversion and Management, Volume 51, Issue 10, October 2010, Pages 1835–1848.

[6] M. Ghazikhani, M.E. Feyz, A. Joharchi, “Experimental investigation of the Exhaust Gas Recirculation effects on irreversibilityand Brake Specific Fuel Consumption of indirect injection diesel engines”, Applied Thermal Engineering, Volume 30, Issue 13, September 2010, Pages 1711–1718

[7] Molina, S., Desantes, J., Garcia, A., and Pastor, J., “A Numerical Investigation on Combustion Characteristics with the use of Post Injection in DI Diesel Engines,” SAE Technical Paper 2010-01-1260, 2010, doi:10.4271/2010-01-1260.

[8] Deepak Agarwala, Shrawan Kumar Singha, c, Avinash Kumar Agarwalb," Effect of Exhaust Gas Recirculation (EGR) on Performance, emissions, deposits and durability of a constant speed compression ignition engine"Applied Energy, Volume 88, Issue 8, August 2011, Pages 2900–2907.

[9] Morteza Fathi, R. Khoshbakhti Saray and M. David Checkel” The influence of Exhaust Gas Recirculation (EGR) on combustion and emissions of n-heptane/natural gas fueled Homogeneous Charge Compression Ignition (HCCI) engines” Applied Energy, 2011, vol. 88, issue 12, pages 4719-4724.

[10] Seungmok Choi, Wonah Park, Sangyul Lee, Kyoungdoug Min, Hoimyung Choi, “Methods for in-cylinder EGR stratification and its effects on combustion and emission characteristics in a diesel engine”, Energy, Volume 36, Issue 12, December 2011, Pages 6948–6959.

[11] Harilal S. Sorathia, Dr. Pravin P. Rahhod And Arvind S. Sorathiya “Effect Of Exhaust Gas Recirculation (EGR) On NOx emission From C.I. Engine” - A Review Study” International Journal of Advanced Engineering Research and Studies E-ISSN2249–8974 IJAERS/Vol. I/ Issue III/April-June, 2012.

[12] V.Manieniyan, S.Sivaprakasam, "Experimental Analysis of Exhaust Gas Recirculation on DI Diesel Engine Operating with Biodiesel ", International Journal of Engineering and Technology Volume 3 No. 2, February, 2013 ISSN: 2049-3444 © 2013 – IJET Publications UK.

[13] K. Bhaskar, G. Nagarajan, S. Sampath, “Optimization of FOME (fish oil methyl esters) blend and EGR (exhaust gas recirculation) for simultaneous control of NOx and particulate matter emissions in diesel engines”, Energy, Volume 62, 1 December 2013, Pages 224–234

[14] B. Jafari, D.D. Ganji and M. Mirsalim “Experimental and Numerical Investigation of the Effect of Exhaust Gas Recirculation on Performance and Emissions of a Dual Fuel (Diesel–Gas) Engine” Australian Journal of Basic and Applied Sciences, 7(7): 668-678, 2013 ISSN 1991-8178