# Numerical Analysis on DI Diesel Engine by Varying Combustion Chamber Geometry

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**Abstract-** The usage of diesel engines compared to gasoline engines was increased recently due to its better performance and reduced emissions. Diesel engines have better brake thermal efficiency and lower carbon monoxide and hydrocarbon emissions but they have a problem of higher particulate and NOx emission. In diesel engines, the combustion chamber geometry plays a major role that it affects the mixing of air and fuel before the combustion starts. The present work is to improve the engine performance and emissions characteristics using different combustion chamber geometries (hemispherical, shallow depth and toroidal). In toroidal combustion chamber geometry, better mixing of air fuel takes place and generates high pressure and hence gives higher brake thermal efficiency. NOx emission is found to be higher while carbon monoxide and soot emissions are lower. It is concluded that for the better performance and reduced emissions, toroidal combustion chamber geometry is found to be the optimum design. Geometry is created by using SolidWorks and STAR-CD is used for the simulation.

*Key Words:* **Combustion chamber geometry, Diesel engine, STAR-CD, Emissions.**

## 1. INTRODUCTION

The use of diesel engines for commercial purpose and gasoline engines for personal purpose was the earlier trend. But it was changed in recent years that diesel engines are used for the personal purpose also. This was mainly due to the better performance and emission characteristics of diesel engine like higher brake thermal efficiency, lower emissions, better power output, less fuel utilization, durability and reliability. Comparatively diesel engines have higher brake thermal efficiency and lower carbon monoxide and hydrocarbon emission. One of the main problems associated with diesel engines is that NOx emission and particulate matter are found to be higher. It affects mainly the design of diesel engines.

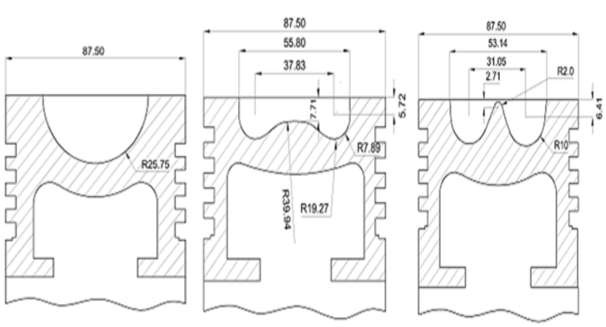
Engine producers are extremely quick to design and build the combustion chamber carefully, since the factors like combustion, performance, emission and production of energy depends on the chamber geometry. Air fuel mixing depends mainly on the combustion chamber geometry. Proper air fuel mixture leads to proper combustion which increases the performance of the engine and power output and emissions from the engine can be reduced to a great extent. Extensive researches have been reported and going on regarding the optimization of combustion chamber designs, fuel preparation and treatment of exhaust gases. For the better performance of a diesel engine, the fuel that was injected has to evaporate quickly and form a mixture which can ignite easily at different regions of the combustion chamber. For complete combustion, the injected fuel has to mix properly with the air and form an ignitable mixture as early as possible. In diesel engines, the time available for the injected fuel to mix with air was very less, so the droplet size determines the efficiency of combustion. Hence the size of the injected fuel has to be as small as possible for better mixing. This can be achieved either by employing a high pressure injector or by the modification of combustion chamber geometry. Turbulence is essential for efficient mixing, evaporation and dissipation of injected fuel droplets. The geometry of the piston bowl can be designed to produce a squish and swirling action which can improve the fuel/air mixture before the ignition takes place. Some earlier numerical studies states that NOx can be reduced by changing the bowl depth.

Combustion of the fuel inside the combustion chamber depend upon many factors like, fuel injection pressure, fuel injection timing, fuel properties, fuel spray pattern, fuel quantity, engine design such as shape of combustion chamber and position of injector, number and size of injection nozzle hole, air swirl and so on. The shape of combustion chamber geometry affects the atomization of fuel and resulting ignition process and is affected by the turbulence made by the cylinder bowl geometry. Air-fuel mixing impacts combustion and emission level in the engine.

The present study describes the introduction of different piston bowl geometries like hemispherical, shallow depth and toroidal combustion chamber geometry into the engine. By using bowl geometries the momentum created will not get destroyed and proper mixing of air and fuel takes place. By using the proper air fuel mixture the combustion will be complete and the power output will be high and the performance of the engine will be increased. Also due to complete combustion the emissions will be lower. The understanding of combustion processes and their influence on engine and emissions performance were described by using STAR-CD tool. The ECFM-3Z (Extended Coherent Flame Model- 3Z) combustion model is selected for the analysis. Combustion and emission characteristics of the fuel n-Dodecane are studied here. The numerical simulation is an effective way to analyse various ideas to improve the engine performance compared to expensive engine experiments and hence it plays an important role in engine research and development.

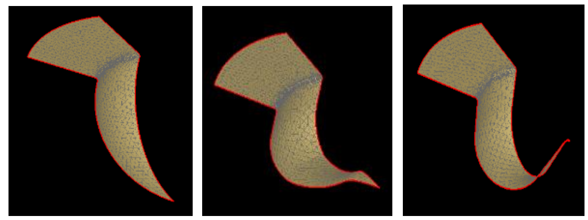
## 2. NUMERICAL MODEL

The CFD simulation begins with modelling the piston bowl geometry. The geometry was modelled by using the SolidWorks 2010 version software. The geometries taken for the analysis are hemispherical combustion chamber geometry (HCC), shallow depth combustion chamber geometry (SCC) and toroidal combustion chamber geometry (TCC). Fig-1 shows the dimensions of the geometries. Meshing of the geometry was done with es-ice (Expert System in Internal Combustion Engine) pro-surf software. Fig-2 shows the meshed geometries. 45° sector of the geometry is taken for the analysis. The main advantage of using a sector mesh is the run time reduction as we are only modelling a fraction of the actual cylinder volume. However, we cannot model the gas exchange phases as the sector mesh cannot handle valve opening and closing events. In addition, the piston bowl is assumed to be axisymmetric so we are unable to model valve pockets or similar features on the piston bowl. Therefore, sector meshing is best suited to modelling the fuel injection and combustion phase of axisymmetric cylinders.




(a) (b) (c)

**Fig -1:** Dimensions of the HCC, SCC and TCC geometries

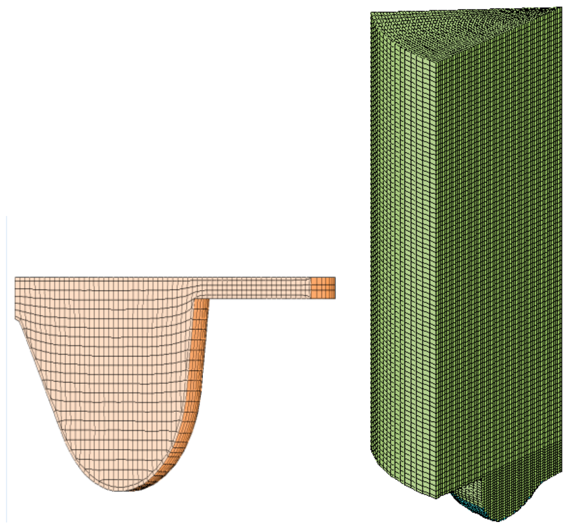


(a) (b) (c)

**Fig -2:** Surface geometry meshed for HCC, SCC and TCC in pro-surf

Fig-3 shows the computational grid when piston is at Top Dead Center (TDC) and the 3D sector mesh when the piston is at Bottom Dead Center (BDC). ECFM-3Z (Extended Coherent Flame Model- 3Z) combustion model is used for the analysis to characterize ignition and combustion. In this model there are three zones such as unmixed fuel zone, the mixed zone containing fuel, air and EGR region and the unmixed air+EGR zone. I-L turbulence model is used for the simulation.

Huh atomization model is used as the primary breakup spray modelling at the nozzle exit. The model is selected based on assumption that atomization is directed by two mechanisms. The first one is gas inertia and the second one is internal turbulent stresses generated within the nozzle. Reitz-Diwakar model is assumed for the secondary break up. This modelling is based on the assumption that fuel droplets become unstable when entering the combustion chamber due to interfacial forces produced by their motion relative to the continuous phase. In compression ignition engines most of the NO emission formation occurs due to temperature inside the cylinder. NO formation from the other sources is very less compared to formations due to temperature. So only thermal NO formation can be described and extended Zeldovich mechanism is selected for the analysis. Soot is an impure carbonaceous particle produced due to incomplete combustion of hydrocarbons.



(a) (b)

**Fig -3:** Piston at TDC and BDC positions for TCC geometry

## 3. ENGINE PARAMETERS AND DETAILS

**Table -1:** Initialization and Boundary conditions

| | |
|---|---|
| Cetane number | 60 |
| Swirl Ratio | 1.81 |
| Equivalence Ratio | 0.85 |
| Exhaust Gas Recirculation | 10 % |
| Turbulence Intensity | 10 % |
| Combustion dome regions | 450 K |
| Piston crown regions | 450 K |
| Cylinder wall regions | 400 K |

**Table -2:** Engine Specifications

| | |
|---|---|
| Engine | Kirloskar, single cylinder, 4 stroke, Vertical, water cooled DI diesel engine |
| Compression ratio | 17.5:1 |
| Cylinder bore | 87.5 mm |
| Stroke length | 110 mm |
| Connecting rod length | 230 mm |
| Engine speed | 1500 rpm |
| Start of injection | 711ºCA |
| Injection pressure | 210 bar |
| Rate of injection | 0.0075kg/sec |
| Injection timing | 23° bTDC |
| Number of holes | 8 |
| Injector hole diameter | 0.00017m |

## 4. RESULTS AND DISCUSSION

### 4.1 In-Cylinder Pressure

The analysis was done on a light duty diesel engine carried out to analyse the effects of combustion chamber geometry on the performance and emission characteristics. The main factors which depend on the performance of the engine are kept constant such as mass flow rate of fuel, compression ratio, injection pressure, calorific value of diesel, engine speed, injection duration etc. The variation of in-cylinder pressure verses crank angle is shown in fig-4. From the graph it is concluded that hemispherical combustion chamber geometry compared to shallow depth and toroidal geometry has the lowest value of in-cylinder pressure. It is mainly due to the fact that, toroidal combustion chamber geometry has more bowl depth and proper swirl can be made compared to other geometries. So proper mixing of air fuel takes place thereby complete combustion occurs in toroidal combustion chamber geometry.

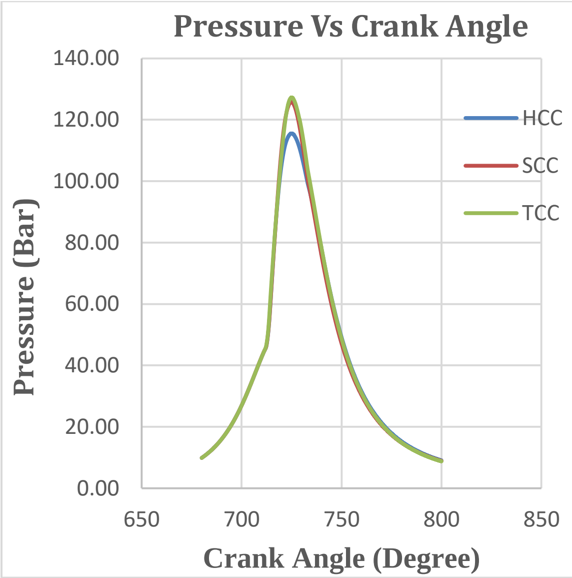



**Fig -4:** In-Cylinder pressure for different combustion chamber geometries

As the geometry changes from hemispherical to toroidal swirl increases and complete combustion occurs and the in-cylinder pressure goes upon increasing. The in-cylinder pressure is found to be maximum for TCC and its value is 127.27bar. The minimum in-cylinder pressure obtained is 115.54bar and is for HCC.

### 4.2 In-Cylinder Temperature

Fig-5 shows the variation of in-cylinder temperature with crank angle for different combustion chamber geometry. In toroidal combustion chamber geometry, the movement of air will be faster due to the bowl shape and hence the swirl will be higher. So proper mixing of air and fuel takes place. So, the mixture formed can be ignited easily and ensures complete combustion. Hence higher in-cylinder pressure is developed and thereby higher in-cylinder temperature. In toroidal geometry, the evaporation will be higher which result in higher heat release rate and higher in-cylinder temperature. Hence, as the geometry changes from hemispherical to toroidal swirl increases and complete combustion occurs and the in-cylinder temperature increases. The maximum temperature obtained is 1933.88 K and is for TCC geometry. The minimum temperature obtained is 1758.25 K and is for HCC geometry.

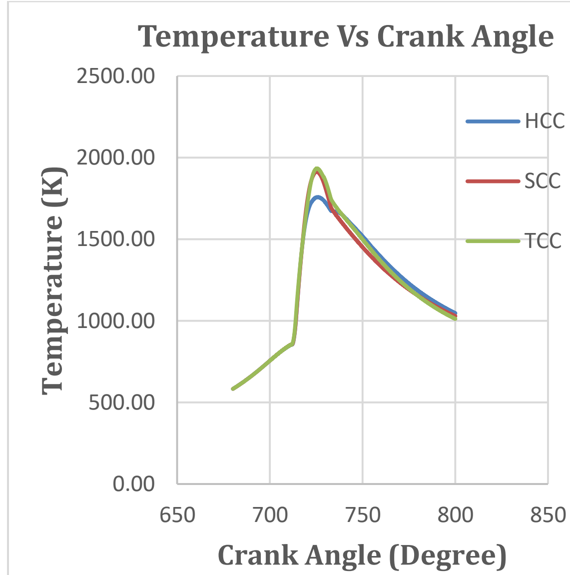



**Fig -5:** In-Cylinder temperature for different combustion chamber geometries

### 4.3 CO Emission

Carbon monoxide emission occurs mainly due to incomplete combustion of the air fuel mixture inside the combustion chamber and is due to the incomplete oxidation i.e., carbon atoms does not change to carbon dioxide. Fig-6 shows the variation of carbon monoxide verses crank angle for different combustion chamber geometries.

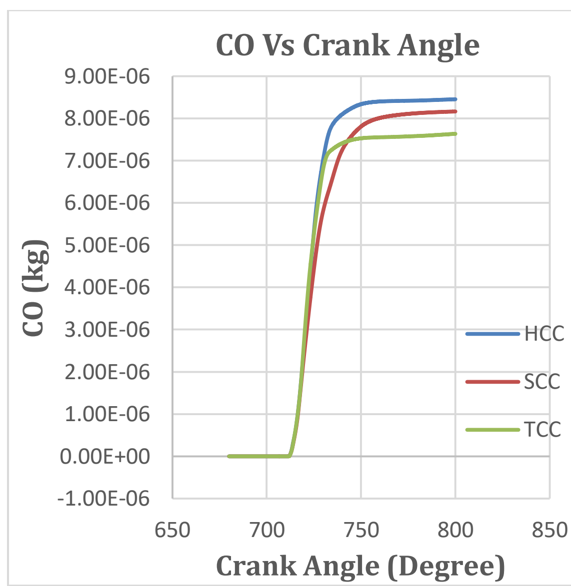
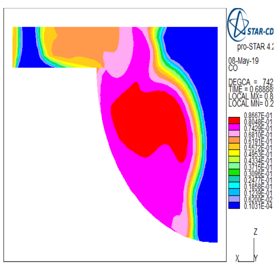
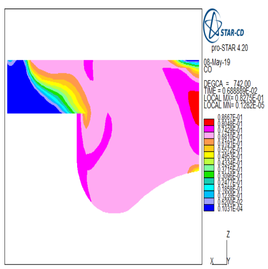



**Fig -6:** Carbon monoxide emissions for different combustion chamber geometries.

The CO emission is found maximum for HCC geometry and found to be less in toroidal combustion chamber geometry. This is mainly because in hemispherical combustion chamber compared to toroidal combustion chamber geometry the air motion inside the combustion chamber was found to be less i.e., swirl created inside the combustion chamber was poor. So proper mixing of air fuel does not take place which results in incomplete combustion. When the combustion chamber geometry changes from HCC to TCC, the air motion inside the chamber is increasing. So proper air fuel mixture can be developed and because of that the oxidation of carbon atoms to carbon dioxide was proper. As a result of this, the emission of carbon monoxide for toroidal combustion chamber geometry was found to be less. From the graph, we can understand that less carbon monoxide emission is for TCC geometry.



(a)



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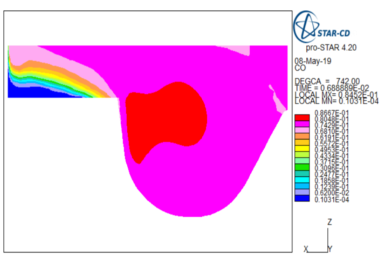


(c)

**Fig -7:** CO emission contours at 742 ºCA for HCC, SCC and TCC geometries.

Fig-7 shows the contours of CO emission at 742ºCA for different combustion chamber geometries. The CO emission was found to be more in hemispherical combustion chamber geometry. This is due to the less swirl motion inside the combustion chamber. Also, CO emission was found to be more near the walls of the cylinder. This happens due to the phenomenon when the fuel particles get sprayed from the injector nozzle, some of the fine fuel droplets get hit on the cylinder wall and decreases its momentum. So, the proper mixing of air fuel does not occur and as a result incomplete combustion occurs and CO emission is formed.

From the contours shown above, we can conclude that the CO emission decreases as the swirl increases thereby complete combustion occurs and is found less in toroidal combustion chamber geometry.

### 4.4 Nitrogen Oxides (NOx) Emission

Fig-8 shows the variation of NOx emission and crank angle for different combustion chamber geometries. The nitrogen oxides produced contain nitric oxides (NO) and nitrogen dioxide ($NO_2$). The NOx formation is highly dependent on the in-cylinder temperature and oxygen concentration. The NOx emission is found to be higher for TCC geometry. This is mainly because in hemispherical combustion chamber compared to toroidal combustion chamber geometry the air motion inside the combustion chamber was found to be less i.e., swirl created inside the combustion chamber was poor.

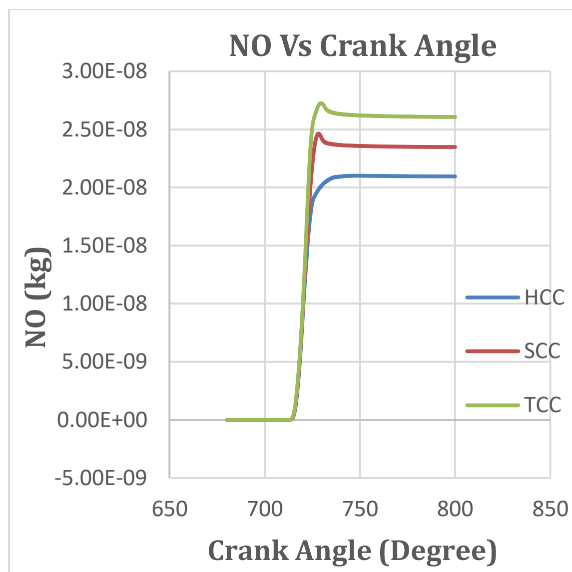
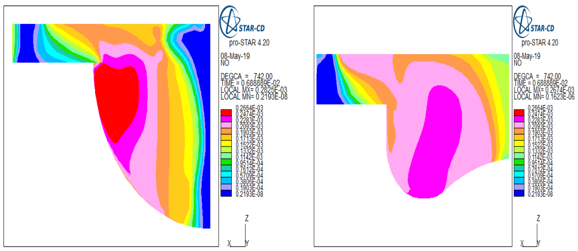


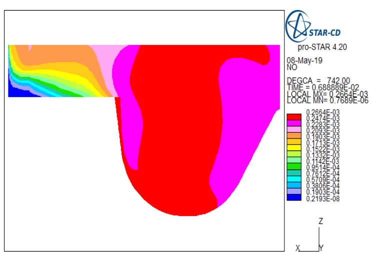

**Fig -8:** Nitrogen oxide emissions for different combustion chamber geometries.

So, compared to toroidal geometry the combustion was not proper in hemispherical and hence the temperature developed is lower. So, the NOx emission will be lower. But in the case of toroidal because of proper mixing of air fuel, complete combustion occurs and the temperature



(a) (b)

developed inside the cylinder will be higher. Hence NOx emission found to be larger in toroidal combustion chamber geometry.



(c)

**Fig -9:** NOx emission contours at 742 ºCA for HCC, SCC and TCC geometries.

NOx emission contours of different combustion chamber geometries are shown in the fig. 9. The NOx emission is found to be higher for toroidal combustion chamber geometry. This is because of the higher combustion temperature obtained from proper combustion due to better mixture and availability of oxygen. NOx formation is found to be less in HCC geometry. This is because of the lower temperature developed inside the combustion chamber

### 4.5 Soot Emission

Fig-10 shows the variation of crank angle verses soot emission for different combustion chamber geometries. The soot emission is found to be lower for TCC geometry and is due to higher in cylinder temperature. The oxidation of soot particles occurs at higher temperatures. Higher temperature is developed in the case of toroidal combustion chamber geometry. This high temperature produced oxidises the soot particles and hence decreases the soot formation. In hemispherical combustion chamber geometry compared to toroidal combustion chamber geometry, the air motion inside the combustion chamber was found to be less i.e., swirl created inside the combustion chamber was poor. So proper mixing of air fuel does not take place which results in incomplete combustion.

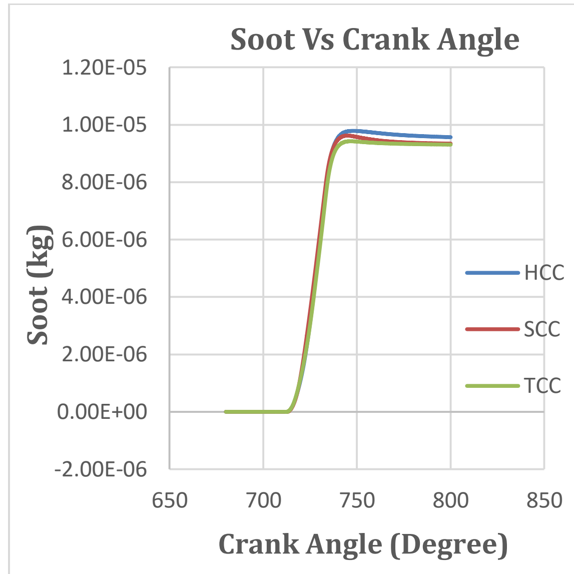
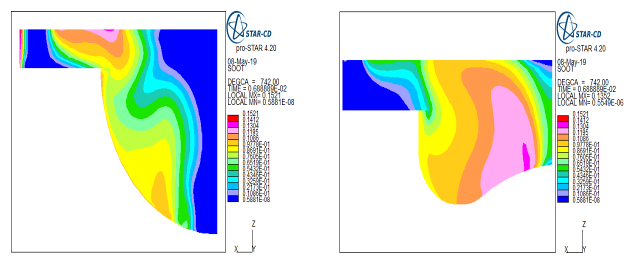



**Fig -10:** Soot emissions for different combustion chamber geometries



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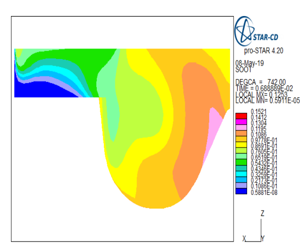

(c)

**Fig -11:** Soot emission contours at 742ºCA for HCC, SCC and TCC geometries.

When the combustion chamber geometry changes from HCC to TCC, the air motion inside the chamber is increasing. So proper air fuel mixture can be developed and because of that complete combustion occurs and thereby higher temperature is developed. This higher temperature oxidises the soot particles. The soot emission is found to be higher for HCC geometry.

Fig-11 shows the soot emission contours at 742ºCA for different combustion chamber geometries. From the contours it can be concluded that the soot emission is found higher for hemispherical combustion chamber geometry. This is because of the incomplete combustion. The lower soot emission is found in TCC geometry. This happened because of the proper mixing of air and fuel inside the combustion chamber. The red colour in the contour shows the region with more soot emission and blue colour shows lower emissions.

## 5. CONCLUSIONS

Numerical analysis was conducted with different combustion chamber geometry (HCC, SCC and TCC) on a Kirloskar diesel engine. The simulation study includes in-cylinder pressure, in-cylinder temperature, CO emission, NOx emission and soot emission. The software used for the analysis is STAR-CD. The results obtained from this study may be summarized as follows.

- The movement of air inside different combustion chamber geometries was studied and found that toroidal combustion chamber geometry have better air swirl motion and turbulence.
- Toroidal combustion chamber geometry has attained higher peak pressure and temperature. The CO and soot emissions are less in toroidal combustion chamber geometry than others.
- The swirl and squish motion in toroidal combustion chamber geometry ensures proper mixing and it results in better combustion thereby increases the combustion chamber temperature. So the NOx emission is found to be high in toroidal combustion chamber geometry.
- By comparing with different combustion chamber geometries, the TCC geometry is found to have better turbulence, air-fuel mixing and air swirl motion. The quality of air movement in the combustion chamber was reduced, correspondingly, by TCC> SCC> HCC.
- The CO, NOx and soot emissions cannot be altogether eliminated and a compromise should be adopted between the performance and emission characteristics. The present study reveals that the performance, combustion and emission characteristics of toroidal combustion chamber geometry are found to be the optimum design for the diesel engine.

## REFERENCES

[1] Renganathan Manimaran, Rajagopal Thundil Karuppa Raj and Senthil Kumar K. (2012) “Numerical Analysis of Direct Injection Diesel Engine Combustion using Extended Coherent Flame 3-Zone Model”, Research Journal of Recent Sciences, Vol. 1(8), 1-9, ISSN 2277-2502.

[2] S.Jaichandar, K.Annamalai and P.Arikaran (2014) “Comparative evaluation of pongamia biodiesel with open and re-entrant combustion chambers in a DI diesel engine”, International Journal of Automotive Engineering and Technologies, Vol. 3, Issue 2, pp. 66 – 73.

[3] Venkata Ramesh Mamilla, M.V.Mallikarjun and Dr. G.Lakshmi Narayana Rao (2013) “Effect of Combustion Chamber Design on a DI Diesel Engine Fuelled with Jatropha Methyl Esters Blends with Diesel”, International Conference On Design And Manufacturing, Procedia Engineering 64, 479 – 490.

[4] S. Jaichandar and K. Annamalai (2012) “Effects of open combustion chamber geometries on the performance of pongamia biodiesel in a DI diesel engine”, Fuel 98, 272–279.

[5] P. Prabhakaran, P. Ramesh, C.G. Saravanan, M. Loganathan, E. James Gunasekaran (2016) “Experimental and numerical investigation of swirl enhancing grooves on the flow and combustion characteristics of a DI diesel engine”, Energy Vol. 115, 1234-1245.

[6] M. N Channappagoudra, Sunil Thaned, K. Ramesh, G. Manavendra (2013) “Optimization of Combustion Chamber Geometry for a Direct Injection Diesel Engine” International Journal of Engineering Research & Technology Vol. 2, 568-577.

[7] A. Ravichandran, K. Rajan, M. Rajaram Narayanan, K.R. Senthil Kumar (2016) “Effect of piston bowl geometry on the performance of a diesel engine using Corn biodiesel and diesel blends” International Journal of ChemTech Research Vol. 9, 105-112.

## ABBREVIATIONS

| | |
|---|---|
| aTDC | After Top Dead Center |
| bTDC | Before Top Dead Center |

| | |
|---|---|
| CFD | Computational Fluid Dynamics |
| CO | Carbon Monoxide |
| DI | Direct Injection |
| ECFM-3Z | Extended Coherent Flame Model-3 Zone |
| EGR | Exhaust Gas Recirculation |
| ES-ICE | Expert System in Internal Combustion Engine |
| HCC | Hemispherical Combustion Chamber |
| NOx | Oxides of Nitrogen |
| SCC | Shallow-Depth Combustion Chamber |
| STAR-CD | Simulation of Turbulent flow in Arbitrary Regions – Computational Dynamics |
| TCC | Toroidal Combustion Chamber |