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Numerical Analysis of Fuel Spray Angle on the Emission Reduction Characteristics in a DI Diesel Engine

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Abstract - *In direct injection (DI) diesel engines fuel spray angle play an important role in the complete combustion of fuel. There will be a chance of incomplete combustion inside the combustion chamber due to the improper mixing of air and fuel that is the air-fuel ratio. This will leads to the emission of harmful pollutants like Oxides of Nitrogen (NOx), Carbon Monoxide (CO), Soot particles. To avoid these circumstances proper engine design, injection pressure, injection timing, swirl ratio and spray angle will lead to proper mixing of air and fuel and thus leads to a complete combustion rate. A numerical study was performed on a direct injection diesel engine at different spray angles to study the emission and the performance of the engine. The performance and the emission characteristics were presented graphically .STAR-CD v4.20 package is used for the analysis purpose.*

Key Words: **Analysis, Caterpillar3401, Diesel Engine, Spray angle, STAR CD**

1. INTRODUCTION

The diesel engine is a type of internal combustion engine more precisely, it is a compression ignition engine, in which the fuel ignited solely by the high temperature created by compression of the air-fuel mixture. Major issue arises on performance of diesel engine are enhanced by proper design of combustion chamber. Flow and combustion chemistry which effect swirl induced by re-entrant piston crown on pollution emission from a single cylinder diesel engine. For more efficient combustion, less emission and soot, HC formation is required [1]. Various studies were done by researchers in the field of IC engines. The main ideology of all those researches was to increase the efficiency. The injection angle is also a very important parameter in the combustion strategies for reducing the emissions and increases the combustion rate [2]. The injection angle leads to a change in the targeting points at the piston wall, and this causes the ignition points to vary. Caterpillar 3401 engine is used as the test engine. STAR-CD is used for analysis. The diesel engine combustion is heterogeneous in nature. Abdul et al, [3] have investigated how the piston bowl geometry and the swirl ratio affects the emission and performance of an engine. Numerical simulations were done on the single cylinder diesel engine. Different configuration of piston with a rectangular cavity and different swirl ratios were considered. Variation in bowl geometry is effected through a corresponding change in ratio of bowl to piston diameter ratio while maintaining the bowl volume, compression ratio, engine speed and the mass of fuel injected constant. From the results we came to a conclusion that as the swirl ratio increases the turbulent kinetic energy which will enhance the quality of the combustion. Variation in the swirl ratios affects the in-cylinder pressure, temperature and the emission parameters which are more significantly for piston geometries with high bowl to piston diameter ratio than with low diameter ratios. The obtained results is that two cases with 70% diameter ratio and 0.5 initial swirl ratio and 55% diameter ratio and 2.5 initial swirl ratio are found to have optimum emission and performance characteristics.

Shahanwaz et al, [4] in their work the combination of the spray angle and the piston bowl geometry on the mixing, combustion and the emission characteristics of a direct diesel engine have analyzed numerically. The piston bowl geometry affects the proper air fuel mixing inside the chamber and there will be a change in the combustion rate and the emission rate. 150°, 155°, 160° and 165° are the 4 spray angles used for the analysis and three different bowl geometries such as Toroidal Re-entrant Combustion Chamber (TRCC), Toroidal Combustion Chamber (TCC) and the baseline Hemispherical Combustion Chamber (HCC) have been considered having same compression ratio of 17.5 and with same chamber volume for all three cases. For the simulation purpose AVL FIRE code was used and the experimental results were validated with the numerical results. They came to a result that 160º will have good performance and bowl geometry of TRCC improves the air motion which reduces the brake specific fuel consumption and soot emission due to improved combustion compared to TCC. Hyung et al, [5] have investigated the effect of the multiple injection strategies and injection angle on the combustion, emission and the performance characteristics in a common rail diesel engine. Various injection strategies with different parameters such as the spray angle, the timing and a single injection or multiple injections were applied. They came to a conclusion that an injection spray angle of 156º will have higher nitrogen oxide emission than the spray angle of 60º did, as the time between the first injection and the second injection increased. Also multiple injections resulted in lower levels of soot and hydrocarbon emissions than a single injection did. A multiple-injection strategy with a dwell time of 20º–40ºcrank angle before top dead center and the first injection at 60º crank angle before top dead center or 50º crank angle before top dead center improved the engine power and lowered the fuel consumption compared with the results for a single injection. Renganathan et al, [6] studied that the behaviour of spray droplet diameter and temperature during the combustion by varying the swirl ratio and injection timing. After the validation and grid and time independency tests, it is found that increase in swirl ratio from 1.4 to 4.1 results in peak pressure rise of 8 bar and an advancement of injection timing from 6º bTDC to 20º bTDC results in increase of peak pressure by 15 %. Premnath et al,[7] In this work, re-entrant combustion chamber with three different fuel injection pressures(200,220and240bars) has been used in the place of the conventional hemispherical combustion chamber for diesel and J20.From the experimental results, it is found that there-entrant chamber improves the brake thermal efficiency of diesel and J20 in all the tested conditions. It is also found that the 20% blend of Jatropha methyl ester showed 4% improvement in the brake thermal efficiency in the re-entrant chamber at the maximum injection pressure. Karuppa et al, [8] they have studied the effect of the swirl ratio in the combustion and the emission characteristics of an engine. Swirl ratios from 1.4 to 4.1 were used for the analysis.ECFM-3Z model is used to model the combustion and the emission in the diesel engine for various equivalence ratio and the swirl ratio. The equivalence ratio from 0.75 to 1.05 affects the reduction of the peak heat release rate. From swirl ratio of 1.4 to 4.1 the turbulent intensity at the TDC is increased by 12%. As the swirl ratio changes from 1.4 to 4.1 the peak pressure, peak temperature, peak heat release rate will increased by 7%, 8.6%, and 31% respectively. Prasad et al, [9] in this study the effect of the swirl for different piston bowl geometry on emission in a diesel engine was studied. Two different configurations were selected for the analysis purpose. It is concluded that the second configuration with a slightly re-entrant combustion chamber and sac-less injection was found to yield lower emission.

2. NUMERICAL MODEL

2.1 Physical Geometry

Modelling of re-entrant piston bowl geometry was done using solid works. Surface mesh generation done by prosurf. Then a 60 °sector mesh was generated in es-ICE. After this, the sector grid is used as a part of STAR-CONTROL for Appling initial condition, boundary condition like beginning temperature, initial pressure and cylinder crown temperature. The base geometry of the model is in the Fig-1. After creating the sector of 60º it is then meshed by using the prosurf tool it is shown in Fig-2. After meshing further computation is done.

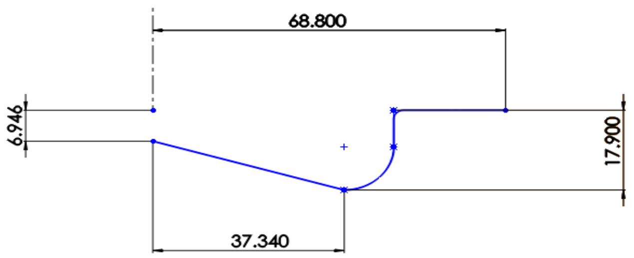

Fig -1: Geometry of the model

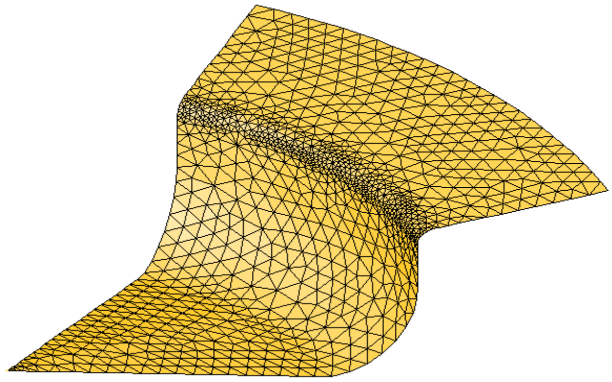

Fig -2: Prosurf meshed geometry

2.2 Computational Procedure

Piston bowl geometry was modelled by using the SolidWorks software. Prosurf is used for the surface mesh generation in STAR-CD. A 60º sector mesh was generated in es-ICE (Expert Systems in IC Engine). Boundary conditions like initial temperature, initial pressure and cylinder crown temperature values are given in STAR-CONTROLS.

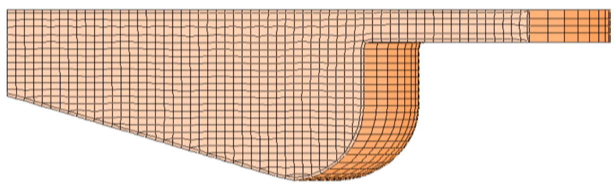

Fig -3: Computational grids at TDC

The Fig-3 shows the computational grids at TDC after that a computational grid at 100°before TDC is obtained, then sector grid is further utilized for applying the fuel properties and injection parameters like mass flow rate, injection temperature, and nozzle hole diameter etc.ECFM-3Z model is used here. k-ε model is used as the turbulence model in analysis purpose. The combustion dome region temperature is set as 450K then the temperature for the piston crown region is set as 450K and cylinder wall temperature is set as 400K. The initial in-cylinder pressure is set as 9.87bar and injection pressure as 900 bar.Different spray angle of 100°, 110°, 120°, 130º were analyzed. From these results best spray angle is selected .

3. ENGINE PARAMETERS & DETAILS

Table -1: Engine Specifications

CATERPILLAR 3401	
Bore	13.719 cm
Stroke	16.51 cm
Compression Ratio	16.1 : 1
Displacement	2.44 L
Connecting rod length	26.162 cm
Squish Clearance	4.14 mm

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Inlet Valve Opening	-32° A TDC
Inlet Valve Closing	-147° A TDC
Exhaust Valve Opening	134° ATDC
Exhaust Valve Closing	29 °A TDC
IMAP	184°K Pa
IMAT	310 k
Piston Shape	Mexican Hat Style

4. RESULTS AND DISCUSSIONS

4.1 Validation

The experimental is in decent agreement with the numerical model, in order to evaluate the precision of the successive predictions. From the figure (Fig. 5) computational in-cylinder pressure settles properly well with the experimental trace. The calculated and experimental in-cylinder pressures 96bar and 92bar respectively. The peak pressure inconsistencies between experimental and computation are 5.2%. The pattern projected by the model is sensibly close to experimental results, although there are still some differences.

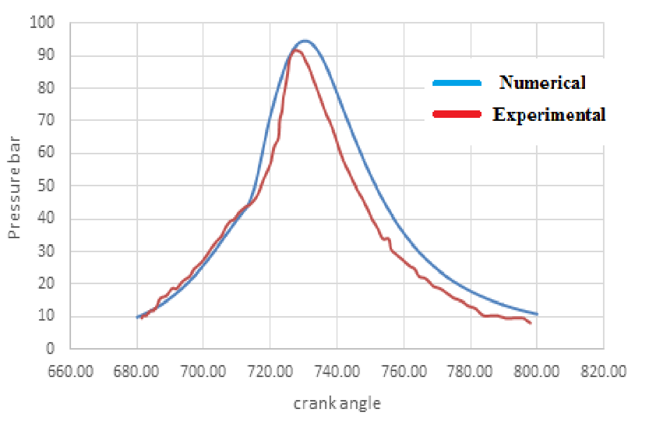


Fig.5. Validation between numerical and experimental graphs

4.2 Cylinder Pressure

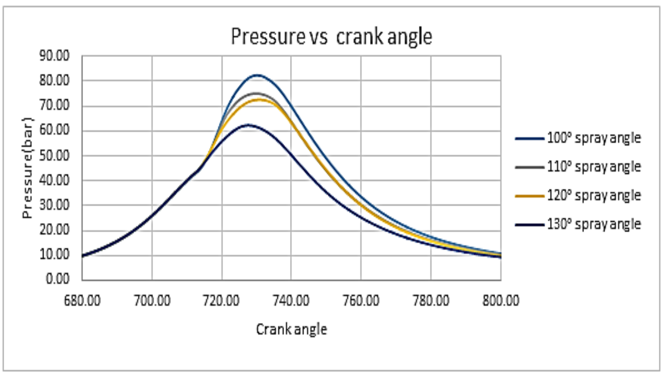


Fig.6. Cylinder pressure with respect to crank angle at different injection pressure of different spray angle.

From the analysis of spray angle of 100°, 110°, 120°, 130º is shown in Fig.6, spray angle of 100º will be having peak in-cylinder pressure whereas 130º will be having least pressure value. Pressure increases from 60bar to 80 bar. The reason behind the decreasing of pressure is due to the impingement of the fuel jet on the linear and the piston surface and that will lead to cooling effect. In the squish region the gas flow will be weaker this also affect the reduction of the pressure. During the 130º spray angle in the squish region the chances of in sufficient oxygen and at the crevice region inflow of the fuel will also take place.

When the spray angle is 100°, wall wetting will be reduced due to the narrow spray angle fuel jet. As the spray angle gets wider the spray from the injector reaches the wall of the cylinder more quickly. The spray angle of 100° will be having more mixing time between the injected spray and the air. When the spray angle is 100º the fuel is directly distributed to the bowl region.

4.3 Temperature

The temperature variation for different spray angle are obtained. From the Fig.7 the spray angle of 130° has the least temperature rate and whereas for 100° has more temperature rate. This is due to when a spray angle of 130º the impingement of the fuel jet on the linear and the piston surface and that will lead to cooling effect, therefore the temperature of the wall will be reduced and will leads to reduce the in-cylinder temperature. The spray angle of 100º will be having high temperature rate. This is because the pressure will be more inside the bowl due to the direct injection of the fuel. So that inside the bowl maximum temperature is produced and proper combustion could be obtained.

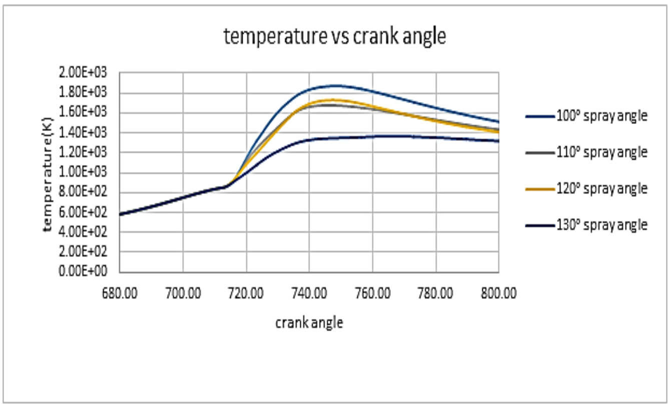


Fig.7.cylinder temperatures with respect to crank angle at different spray angle

4.4 NOx Emission

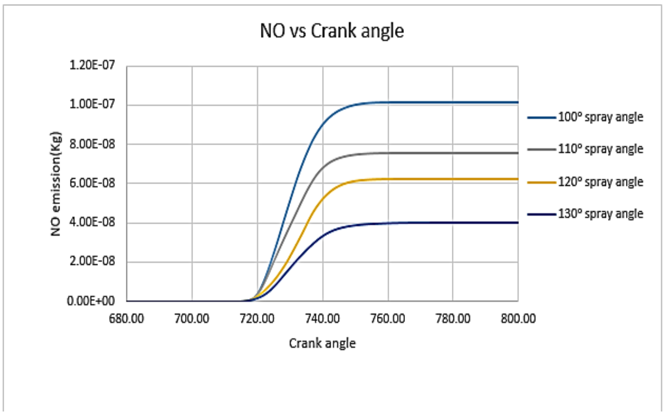
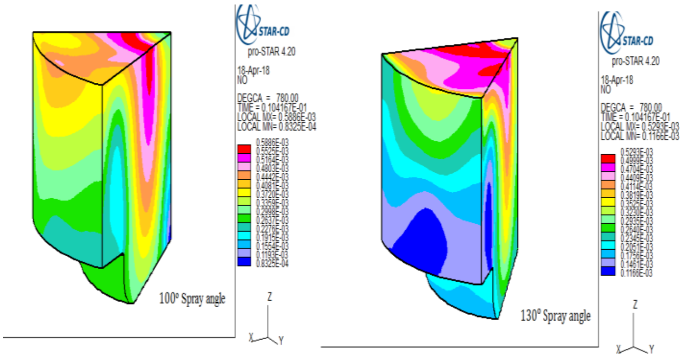


Fig.8.NOx emissions with respect to crank angle at different spray angle pressure.

There are significant difference in the amount of the NOx emission of two spray angles. From the Fig 8 the piston with spray angle of 100º the fuel has sufficient time to turbulently mix with the incoming air in the bowl a short period before ignition, the injected fuel probably avoids evaporation caused by the lower temperature relative to the TDC. A rich fuel region is created in the areas near to the bottom of the bowl consequently followed by combustion at high temperature. On the other hand the NOx emission will be less for the 130° spray angle.



(a) (b)

Fig.9. NOx contour at 780° crank angle at 100° and 130ºspray angle

The Fig.9 shows NOx emissions variations versus crank angle at different spray angle. Figure shows NOx contour at 780º crank angle at 100° and 130º spray angle respectively. NOx is created mostly from nitrogen in air. At low temperatures atmospheric nitrogen exists stable diatomic molecule. Therefore, only very small trace amounts of oxides of nitrogen are found. However, at very high temperatures those occur in the combustion chamber of an engine, some diatomic nitrogen N_2 breaks down to monoatomic nitrogen (N) which is reactive. As spray angle reduces in-cylinder temperature and pressure increases. So the NOx emission also increases.

4.5 Soot Emission

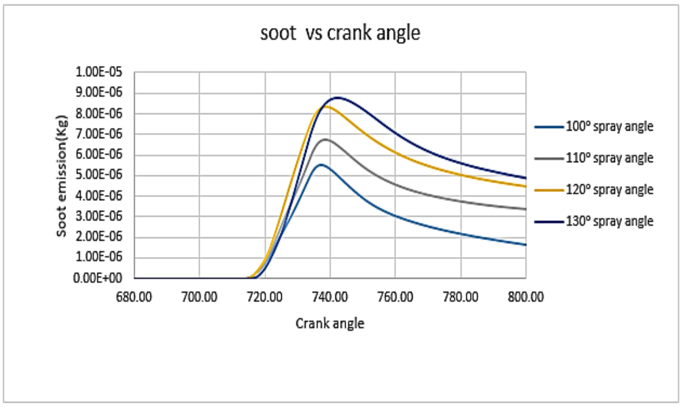
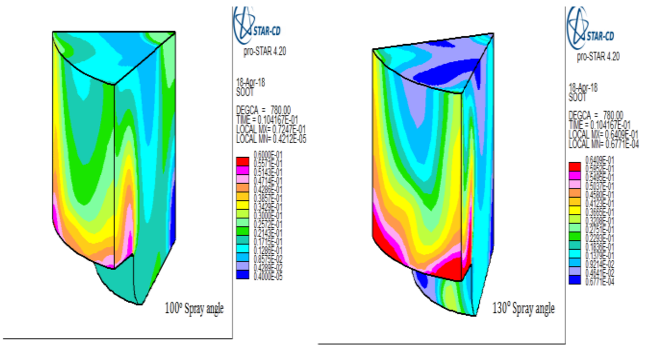


Fig.10. soot emissions at different spray angle.

The piston bowl geometry and the impinging position affects the soot formation inside the engine. The fuel injected at 130º of the injector approaches the top side of the piston bowl and hence forth flows along the piston structure. Fig.10. shows the soot emission at 130º spray angle will be having more emission rate and least for 100º spray angle. Furthermore the flow creates a well-mixed mixture, though the fuel injected by the 100° injector leads to relatively many fuel rich regions after making contact with the piston wall. Thus the 100º injector created lower soot emissions relative to 130° injector due to the locally fuel rich regions. The fig.11 show the changes in contour of soot emission at 780º crank angle for 100º and 130º spray angles. Soot is originated from the agglomeration of very small particles of partly burned fuel, partly burned lube oil, ash content of fuel oil and cylinder lube oil and water.



(a) (b)

Fig.11. Soot contour at 780º crank angle for 100° and 130° spray angles.

4.6 Carbon Monoxide Emission

The effect of the emission of the CO emission of different spray angle are illustrated in the Fig.12. For the optimum spray angle of 100º the lowest CO emission and best fuel conversion efficiency are observed. At higher spray angle the flow structures formed impede mixing, and lead to trapping of partially burned fuel with the bowl. For 130º spray angle there will be an existence of wall film on the top of the piston which may lead to the increase of CO emission. Finally the possibility that enhanced pre-combustion turbulence by proper implementation of spray angle will lead to the reduction of the CO emission. The principle effect of turbulence is to increase the flame surface area.

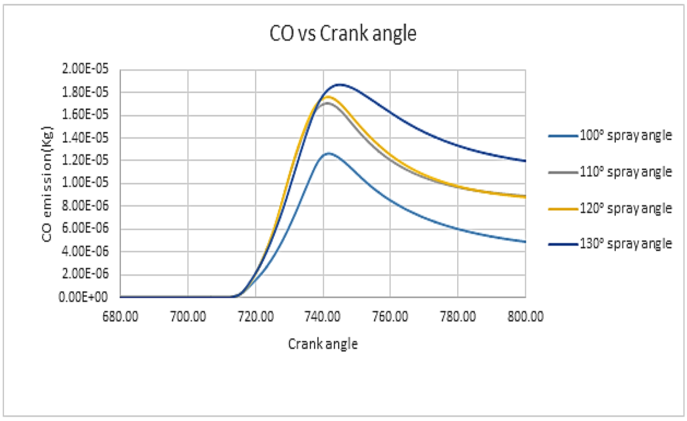
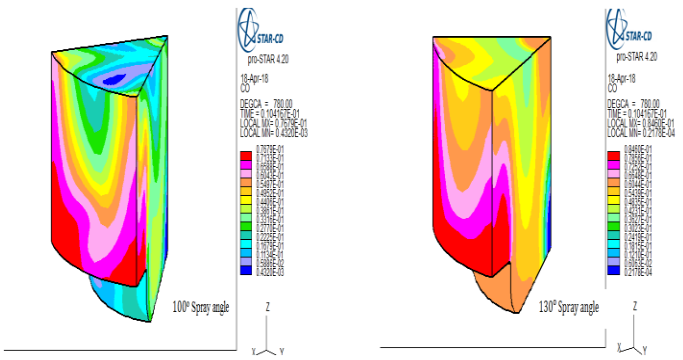


Fig.12. CO emissions at different spray angles



(a) (b)

Fig.13. CO contour at 780 º crank angle at 100° and 130º spray angles.

Contour obtained for the emission of CO is shown in Fig.13. Carbon monoxide results from the incomplete combustion where the oxidation process does not occur completely. As the injector angle reduces the formation of unburned gases reduces. So for 100° spray angle the CO emission will be less. This is illustrated in the above graph.

5. CONCLUSION

CFD study is presented to analyse the effect of modification of the spray angle at constant compression ratio on the fluid flow, combustion, emission and engine operation. The results were discussed elaborately and the point of conclusion are as follows,

- It was found that reducing the spray angle provides better uniformity in air/fuel mixture which results in higher peak pressure.
- By this proper mixing complete combustion will take place which results in perfect emission reduction and better engine performance.
- From the analysis it is found that the 130º spray angle will leads to wall wetting condition which results to cooling of the cylinder wall which leads to incomplete combustion.
- For 100º spray angle the fuel is directly injected to the chamber so that the wall wetting condition could be avoided and leads to complete combustion of fuel. From these observation it is concluded that for a 100º spray angle goo combustion rate and emission reduction could be attained properly.

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