Numerical Simulation on Effect of Spray Cone Angle on Emissions in Diesel-Engine using AVL-FIRE

Gopal Kumar Deshmukh, Ameenur Rehman, Rajesh Gupta

Abstract: The in-cylinder flow dramatically affects combustion performance and emission characteristics of a compression ignition engine. The spray cone angle is among the most critical factors affecting mixture formation, combustion and emissions in a direct injection diesel engine. We have used three-dimensional computational investigations on spray cone angle-induced emission pattern of V-type DI engine under AVL-FIRE and ESE simulation interface. Four spray cone angles of 120°, 130°, 140°, and 150° were used for simulation purpose. The findings from the three-dimensional AVL-FIRE simulation confirm the influence of spray angle on optimal air-fuel mixing and, hence, combustion. Spray cone angle of 140° gave better engine performance in terms of lower CO and soot emission, but increased NO emission was observed due to improved combustion.

Keywords: Computational Fluid Dynamics, Spray cone angle, Emission, AVL-Fire Code

I. INTRODUCTION

In a compression ignition (CI) engine or diesel engine, the fuel under higher velocity is injected into the cylinder only towards the end of a compression stroke. Energy is derived from the ignition of the atomized fuel when contacted with this hot compressed air. It is different from the spark ignition (SI) engine where premixed air and fuel are introduced into the cylinder, and the combustion process is ignited by a spark plug. Diesel is more energy-dense than petrol, and the superior thermal efficiency of diesel engine makes them more fuel efficient than petrol engine. Due to the presence of large, long-chain hydrocarbons, diesel has more energy than a comparable quantity of petrol; energy density is 36.9 MJ/liter in diesel compared to 33.7 MJ/liter in petrol. Thermal efficiency, which is the energy output per unit volume of fuel, determined by the compression ratio and stoichiometric air-to-fuel ratio is far more competent in diesel engines. The absence of throttle plates in CI engine also positively impacts output. Based on power output values, CI engines can be categorized into small (<188 kW), medium (188–750 kW), and large (>750 kW). Characteristics of the cylinder, such as number and arrangement, influence engine capacity. Straight (inline) models are more used in light-to-medium duty engines. V-type arrangements are more stiffer and compact and are used in aircraft, marines, powered motorized vehicles, and high-performance models where reliability and durability are crucial. These engines can produce more torque at lower speed ranges probably because of the power stroke coming from double sides of the crankshaft. However, diesel engines contribute more pollutants to the environment than other engines. Unlike the homogeneity of petrol-air mixture in SI engines, diffusion-controlled combustion in CI models cause stratification between fuel and air, creating more oxides of nitrogen (NO_x) and particulate matters (PM). Recirculation of exhaust gas into the combustion chamber, referred to as exhaust gas recirculation (EGR), can significantly reduce emissions. The burnt gas is not involved in combustion, but as the proportion of combustible elements declines, EGR reduces peak cylinder temperature and, thus, NO_x formation. The temperature rise is also checked because of the higher specific heat capacity of exhaust air than fresh air. Additionally, the gas to be circulated can be passed through an EGR cooler to reduce its temperature, and this high density gas allows effective utility of this technique. Piston bowl geometry, spray angle, fuel injection pressures, and variable fuel injection timing are the main input parameters in a diesel engine that translate to better diffusion atomization of fuels and in-cylinder air movements, affecting engine efficiency and emissions [1]. Through its influence on spray characteristics and hydrodynamic cavitation, the injector nozzle, specifically the nozzle geometry, is a critical factor in fuel atomization process, ensuring proper air-fuel ratio for combustion [2]. There are many scientific reports on various features of piston geometry and its implications on the formation of mixture and combustion phenomena [3-4]. Jaichandar et al. [5] examined the effect of bowl geometry configurations, such as Hemispherical Combustion Chamber, Toroidal Combustion Chamber, and Shallow Depth Combustion Chamber, and injection timing on the performance characteristics of a bio-diesel-fuelled DI compression engine. The Toroidal Combustion Chamber piston geometry was shown to have higher brake thermal efficiency and reduction in the discharge of PM, unburned carbon monoxide (CO) and hydrocarbon (HC). However, due to better combustion efficiency, a small increase in the production of NO_x was observed. Macroscopic spray characteristics, such as spray angle,

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break-up length, core area, penetration., etc., as well as microscopic features, including size and spatial distribution, mean diameter and turbulence, affect diesel spray combustion and engine performance. Orifice geometry significantly impacts spray characteristics, as compared to circular ones. The elliptical spray had lower peak concentrations and smaller rich core regions [6]. Modifications in spray angle and shape of the piston bowl were shown to minimize wall impingement and soot emission [7].There are not many reports on nozzle spray angle or piston bowl geometry-induced changes in fuel efficiency and emission pattern in a diesel engine, which is, hence, the major objective of this work. By using computational fluid dynamics code, we have investigated the impact of spray cone angle on CO, NO_x and soot discharge. The AVL-FIRE code implemented for the study included modeling of the impact of fuel against the cylinder walls as well as heat transport upon film vapourization.

II. MODEL DESCRIPTION

SCC (Shallow depth Combustion Chamber) piston bowl geometry of the combustion chamber with four different spray cone angles was taken into account. They have four cylinders in a V-type configuration. The connecting rod length and crank radius were adjusted to have a stroke equivalent to 210 mm. The clearance was 8.5 mm based on baseline case. The engine involved medium load at a speed of 1800 rpm. Computational domain of SCC piston bowl geometry of combustion chamber considered designs at top dead centre (TDC) position is depicted in Figure 1.

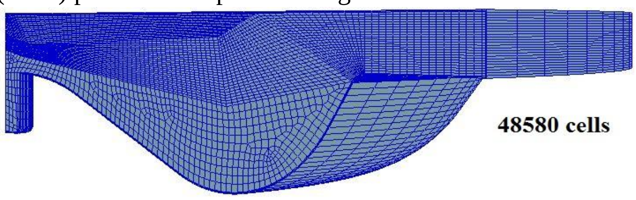

Fig. 1. Computational domain of SCC piston bowl geometry with the number of cells at TDC.

Three densities of mesh, i.e., fine, medium, and coarse grids were compared with respect to pressure curve and net HRR against crank angle to demonstrate optimum mesh resolution for simulation. As seen in Figure 2, the adoption of medium grid density with 48580 cells at TDC illustrated sufficient mesh independency of results. The application of more cells in the meshing process would affect simulations in terms of computational cost and accumulation of errors.

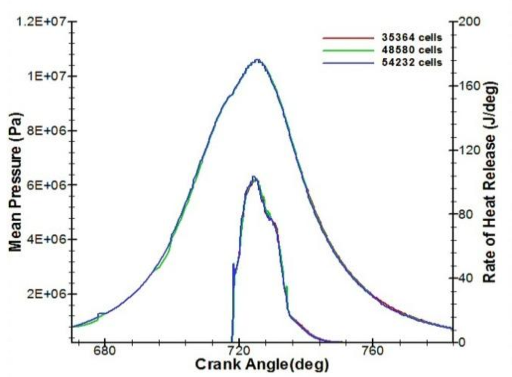

Fig. 2. Grid independency test of mean pressure and net HRR variation with different mesh sizes

A. Sub-Model

Three-dimensional computational investigations for V-type (direct-injection) DI engine were done using AVL-FIRE and ESE simulation interface. Table I enlists the submodels used in the code on the basis of previous reports. 3-D ESE diesel interface code was used for creating the meshes; fluid dynamic simulation was done using AVL-FIRE™ software. Calculations within each computational cell were performed as per the finite volume method (FVM) to preserve conservative properties, whereas discretization of the momentum equation was done by the finite difference method (FDM). Spray, combustion, and emission modules are explored in commercial codes for a better appreciation of the in-cylinder mechanisms within the engine.

Table-I: Computational submodels for engine operational condition

Head temperature	550.15 K
Piston temperature	575.15 K
Cylinder temperature	475.15K
Spray break up model	Modified Kh-RT
Combustion model	ECFM-3Z
Turbulence model	k-ζ-f
Evaporation	Dukowicz
Soot	Kennedy/Hiroyasu/Magnussen
Fuel injection quantity	31.3 (mg/cycle)
Residual gas ratio	0.5
Initial pressure	0.1 MPa
Initial temperature	300 K
Injection valve closed	52° CA ATDC
Exhaust valve opened	110° CA ATDC

III. NUMERICAL SIMULATION

In this study, a heavy-duty V type four-cylinder DI diesel engine having a compression ratio of 16.4:1 and a swept volume of 438 cm^3 was used. The operational conditions of the specified V type engine are presented in Table II. AVL-FIRE code generated data for the baseline piston bowl geometry case is compared with experimental data, as shown in Figure 3 for validation. The computational results conform to the conclusions derived from the experiments of Hawley et al., 2001 [8]. A significant match between the calculated and measured cylinder pressure curve can be confirmed with this study.

Table- II: Engine operational condition.

Bore × stroke	170 × 210 mm
Connecting rod	110 mm
Displacement	438 cm^3/cylinder
Fuel type	Diesel
Compression ratio	16.4:1
Number of nozzles	4
Injection start timing	3° CA BTDC
Injection spray angles	120°,130°,140°, and 150°

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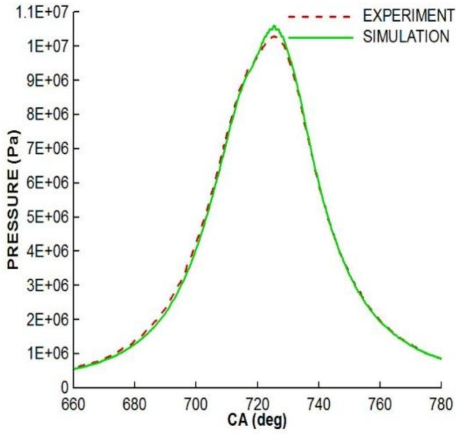


Fig. 3. Comparison of experimental and simulated results for the pressure curve [8]

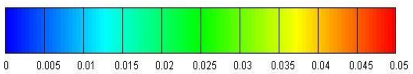
IV. RESULTS AND DISCUSSION

Spray atomization and air-fuel mixing in CI engines can be optimized by tinkering the piston bowl geometry to enhance pre-combustion turbulence [9]. Emission characteristics in the diesel engine are influenced by mixture formation. To have a better understanding on the emission formation characteristics versus crank angle curves for SCC, piston bowl geometry is compared at spray angles of 120°, 130°, 140° and 150° under medium load operation.

A. Carbon Monoxide Emissions

CO is generally low in exhaust emission due to lean mixture in diesel engine. It is formed when the excess-air factor (λ) falls below 1.0 (rich mixture), leading to incomplete oxidation of carbon. This simulation was conducted to determine the emission characteristics due to spray formation [10].

Mean CO mass fraction



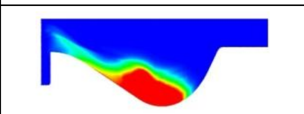
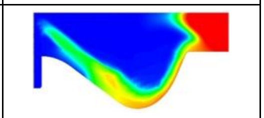
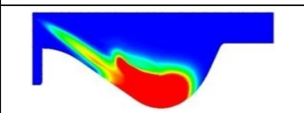
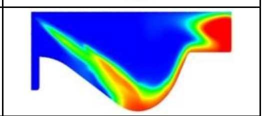
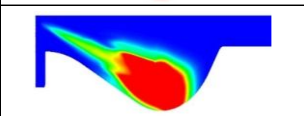
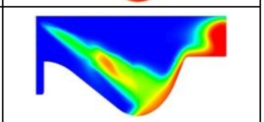
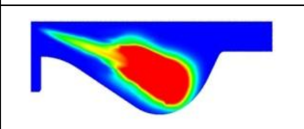
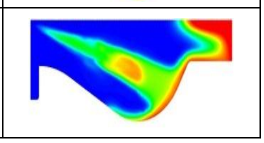
Spray Cone Angle	TDC	10° ATDC
120°		
130°		
140°		
150°		

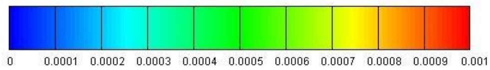
Fig. 4. Contours of CO emission for different spray angles at TDC, and 10° ATDC.

Figure 4 depicts the contours of CO emission distribution for spray angle 120° to 150° CA at TDC, and 10° after TDC. The lowest and highest CO mass fractions were achieved for 140° and 120° spray cone angle, respectively, at the end of the combustion process. The maximum values were observed at 0.0044 and 0.003 of mass fraction, respectively.

B. Mean NO mass fraction

NO_x emissions in engine cylinders show combustion quality. Higher NO_x emissions show better combustion, which leads to better mixing in diesel engines. Controlling NO_x formation in diesel engines without EGR is a difficult task [11].

Mean NO mass fraction



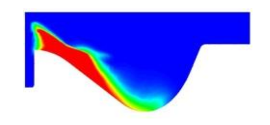
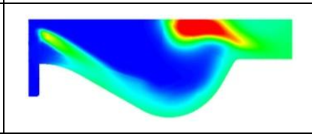
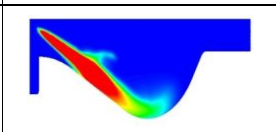
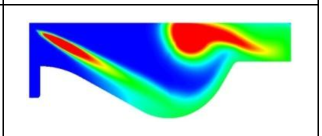
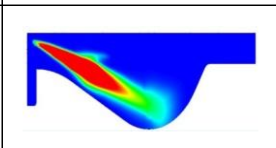
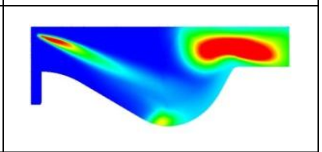
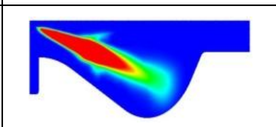
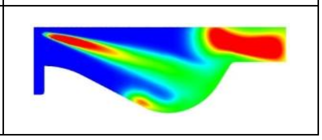
Spray Cone Angle	TDC	10° ATDC
120°		
130°		
140°		
150°		

Fig. 5. Contours of NO distribution across the chamber for different spray angles at TDC, and 10° ATDC.

Contours of NO distribution over the four different spray angle 120° CA to 150° CA for two different positions, TDC and 10° ATDC, are shown in Figure 5. The 140° CA and 120° CA spray angles corresponding to the highest and lowest contents of emission, with 0.00029 and 0.00017 mass fraction, respectively. This can be clearly seen from the contours of NO emission.

The bowl geometry has probably enhanced the pre-combustion turbulence through its impact on the flow behaviour within the cylinder, expressed mainly as swirl, tumble, squish, Turbulent Kinetic Energy for small scale motions, etc., favouring high-temperature combustion and NO emission.

C. SOOT

Unburnt carbon particles are referred to as soot. In a diesel engine, ignition delay is very less since diesel has a high cetane number and low self-ignition temperature than petrol [12].

SOOT

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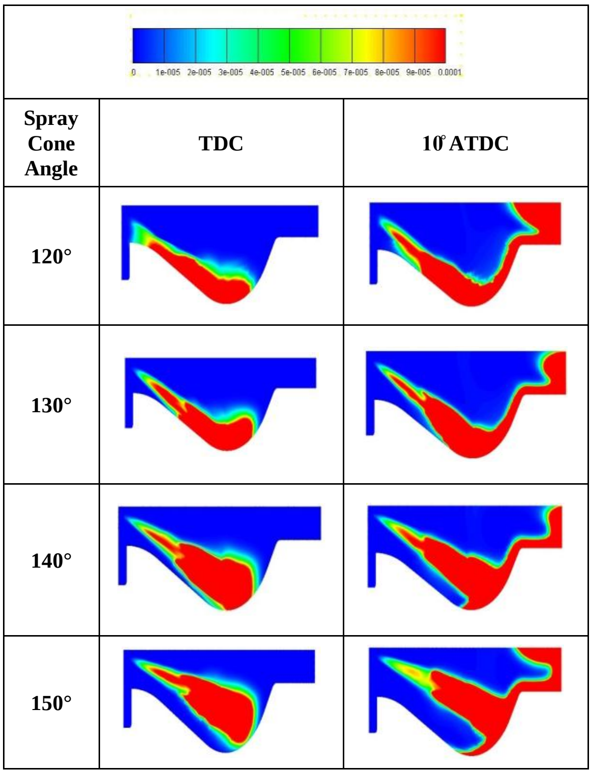

Fig. 6. Contours of SOOT emission distribution across the chamber for different spray angles at TDC, and 10° ATDC.

However, combustion may occur as the fuel continues to be injected creating fuel-rich zones that produce soot upon pyrolysis. Incomplete combustion is more pronounced with high speed when the air-fuel ratio falls below optimum. Contours for soot distribution are depicted in Figure 6 at TDC and 10° CA ATDC positions. Soot formation was maximum at 120° cone angle, while, at 140°, it was observed to be minimal. The contours of soot formation depicted in Figure 6 show that mixture formation process between diesel and compressed air was highly swirling flow, which resulted in high soot at 120°.

V. CONCLUSION

In the SCC piston bowl combustion chamber configuration, five types of spray cone angles were simulated, and all operating conditions were set the same for all diesel engine cases. The major conclusions are as follows:

1) Spray cone angle fuel injection showed the effects on mixture formation and, thus, emission characteristics.
2) The findings showed that the SCC piston enhanced NO emission, whereas CO and HC emissions were reduced at 120° cone angle.
3) SOOT emission was found to be high at 120° cone angle.
4) NO emission was found to be high at 140° cone angle.
5) Furthermore, the spray orientation started in combustion parameters will be included in further studies.

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