Simulation of injection angles on combustion performance using multiple injection strategy in HSDI diesel engine by CFD

Konkala Bala showry[1] Dr.A.V.Sita Rama Raju[2]

1. Associate professor DVR College of Engineering and Tech Hyderabad A.P. INDIA (Corresponding Author)
balakshowry@yahoo.com

2. Professor JNTUCEH Hyderabad A.P. INDIA

Abstract

This research focused on the effects cone angle using split injection on combustion in a direct injection diesel engine. Simulation has been carried on two different cone angles **150**and **70**degrees. Duration of injection, starting of injection, dwell, and spray cone angle and nozzle hole diameter are some of the important parameters which improves the engine performance consequently pollution levels gets decreased. As far as cone angle is concerned the cone angle should be optimum and nozzle diameter should be optimized so as to achieve maximum efficiency for an optimum pressure. Even though EGR plays a major role in reducing pollution levels to some extent in terms of NOx and soot, in this work EGR has been considered as zero percentage because as EGR increases particulate matter. It also dilutes the fresh charge which has been taken inside the engine. Split injection takes care of reducing particulate matter without increase in NOx levels .In this research simulation for two different cone angles have shown good agreement with experimental results.

Key words: Split injection, Dwell, Start of injection, Duration of injection, Spray cone angle EGR, CFD

1. Introduction

Diesel engine is widely used in heavy duty transport applications. Diesel engine is more fuel efficient than spark ignition engine on the other side they have relatively higher emissions and noise levels. Diesel engine manufacturers have to address these problems to meet current and future government regulations which limit particulate and NOx emissions, while maintaining a quite efficient engine to satisfy the consumers. Particulate matter and NOx production along with engine noise highly depend on the combustion process Therefore precise control over the fuel injection and spray formation is essential in making improvements to the combustion process .The optimum pressure and optimum nozzle diameter increases the performance and consequently reduces the particulate matter with the better atomization and fuel- air mixing. This in turn unfortunately increases NOx because of high temperature. To improve the performance and to reduce the NOx –particulate formation without scarifying the fuel consumption, it is important to understand the relationships between various injection parameters and how they affect the combustion process. Along with the injection pressure and nozzle diameter other injection parameters like such as nozzle hole L/D ratio, rate of injection profile , effect of fuel spray , spray characteristics , that may affect the droplet size, spray penetration exit velocity and spray cone angle. Use of multiple injections can reduce particulate emissions by as much as a factor of three without increasing NOx emissions. This will be done by better mixing later in the cycle. Optimizing the injection pressure, injection angle and optimizing the nozzle diameter has proven to be an effective way to reduce particulate emissions and consequently improves the engine performance. Multiple injection strategies have been reported for simultaneous reduction of NOx and PM in a large bore direct injection diesel engine [1, 2, 3].Small bore diesel engines results shown by Nehmer and Reitz [2] that pulsated injection might provide a method to reduce PM and allow for reduction of NOx from controlled pressure rise. The effectiveness of double, triple and rate shaped injection strategies to simultaneously reduce NOx and PM was also evaluated. Numerical simulations were carried out to explore the mechanism of soot and NOx reduction for multiple injections [4]. Multiple injection strategies have a similar effect to the restarted single injection on NOx reduction. Reduced emissions are due to the fact that the soot producing rich region is **not replenished** when the injection pressure is terminated and restarted. Zang investigated the effect of [5] pilot injection on NOx, Soot emissions and combustion noise in a small diesel engine, soot emission was seen relevant to the pilot flame and reducing the pilot flame at the main injection starting time can reduce soot emissions. By optimizing pilot injection timings and quantity maintaining and dwell between main and pilot injections simultaneous reduction of NOx and PM was obtained in a HSDI diesel engine [6].It was also shown that simultaneous reduction of combustion noise and emission is possible by the influence of the pilot burned gas through minimizing the fuel quantity by advancing the pilot injection timing [7].Combustion concepts like homogeneous charge compression ignition combustion have been shown to be effective for NOx and PM reduction. The concept of HCCI was applied initially to spark ignition engines because of its volatility property for better homogeneous mixture, where as in diesel engines this concept has been delayed as diesel has low volatility. With the concept of multi pulse injection the problem of homogeneous mixture in diesel engines could be solved and the same has been applied for high speed direct injection diesel engines effectively. Hashizume [8] proposed a low soot solution called multiple stage diesel combustion for higher load operating conditions. Although, soothing luminous flame was observed, this luminous flame disappeared quickly and most of the soot was oxidized rapidly smoke and NOx were reduced. SuW ,Lin T,Pei Y.A have done work[9]on multi pulse HCCI diesel engine ,they used multiple short injection pulses for early injection and followed by main injection near top dead center and they found that for very early injection a great increase in Hydrocarbon emission was seen. Hasegawa and Yanagihara employed two injections called uniform bulky combustion system .The first injection was used to form a pre- mixture. The second injection was used as an ignition trigger. The ignition of premixed gas could be controlled by the second injection when the early injection maintained a low temperature reaction.

2.0 Methodology Model formulation

The computer code used in this study was **FLUENT**. The code can solve unsteady, compressible turbulent flows with combustion and fuel spray, and have been used for the computations of various internal combustion engines The code uses a finite volume methodology to solve discredited Nervier-strokes equations. RNGK-έ was used in this study. It could predict more realistic large scale flame structures compared with the K-έ model. The RNG K-έ model is formulated as

$$\frac{\partial \rho \kappa}{\partial t} + \nabla\cdot(\rho u k) = \frac{2}{3}\rho k \nabla\cdot u + \tau : \nabla u + \nabla\cdot(\alpha_k \mu \nabla k) - \rho\varepsilon + W^s \qquad (1)$$

$$\frac{\partial \rho \varepsilon}{\partial t} + \nabla\cdot(\rho u \varepsilon) = -\left[\frac{2}{3} C_1 - C_3 + \frac{2}{3} C_\mu C_\eta \kappa \nabla\cdot u\right]\rho\varepsilon\nabla\cdot u + \nabla\cdot(\alpha_\varepsilon \mu \nabla\varepsilon) + \frac{\varepsilon}{\kappa}\left[(C1-C\eta)\tau:\nabla u - C_2\rho\varepsilon + C_s W^s\right] \qquad (2)$$

Where C_3=

$$\frac{-1+2C_1-3m(n-1)+(-1)\delta}{3}\frac{\sqrt{6}C_\mu C_\eta \eta}{} \qquad (3)$$

$\delta = 1$; if $\nabla\cdot u < 0$ $\delta = 0$; if $\nabla\cdot u > 0$ And

$$C\eta = \frac{\eta(1-\eta/\eta_0)}{1+\beta\eta^3} \quad \eta = S\frac{\kappa}{\varepsilon} \quad S = (2 S_{ij} S_{ij})^{1/2} \quad S_{ij} = \frac{1}{2}\left(\frac{\partial u_I}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$$

In equation (1)-(3) k and ε are turbulent kinetic energy and its dissipation rate .ρ, u,τ and μ are density, velocity, stress tensor and effective viscosity respectively.η is the ratio of the turbulent –to mean – strain time scale . S is the magnitude of the mean strain. m =0.5, and n =1.4.The C3 term accounts for the non- zero velocity dilatation which is closed.

3.0 Governing equations The governing equations of gas flow consist of mass, momentum and energy conservation equations turbulence equations, gas state relation equations. To take care of physical modeling k-ε turbulence model is employed. The various equations, which are solved**:**

3.1 Continuity $\frac{\partial p}{\partial t} + \nabla(\partial U) = 0$

3.2.Momentum

$$\sigma = \mu\left[\nabla U + (\nabla U)^r\right] + \lambda\nabla .UI$$

1

3.3 Turbulence Model

3.3.1K-Equation

$$\frac{\partial(\rho k)}{\partial t}+\nabla(\rho Uk)=-\frac{2}{3}\rho k\nabla U+\sigma\nabla U$$

$$+\nabla.[(\frac{\mu}{pr_k})\nabla k]-\infty\rho\varepsilon$$

3.3.2εEquation

$$\frac{\partial(\partial\varepsilon)}{\partial t}+\nabla.(\rho U\varepsilon)=-(2c_{\varepsilon1}/3-c_{\varepsilon3})\rho\varepsilon\nabla.U$$

$$+\nabla.\left[(\frac{\mu}{pr_\varepsilon})\nabla\varepsilon\right]+\frac{\varepsilon}{k}\left[c\varepsilon_1\sigma:\nabla U-c\varepsilon_2\rho\varepsilon\right]$$

The quantities $c\varepsilon_{1,}c\varepsilon_{2,}c\varepsilon_{3,}pr_{\varepsilon,}pr_k$ are constants whose values are determined from experiments and some theoretical considerations, a feature that establishes certain universality. Standard values of these constants are often used in engine calculations as given below.

$$c\varepsilon_1=1.44c\varepsilon_2=1.92c\varepsilon_3=-1, pr_k=1.0,$$

$$pr_\varepsilon=1.3$$

4.0 Mathematical models4.1 Spray model

Spray models used in this study is WAVE break up model suggested by Reitz and could be summarized as follows. [10] Liquid break up is modeled by postulating the new drops are formed (with drop radius r) from a parent drop or blob (with radius a) with stripping.r_{new} $=B_0.\Lambda$ (4)Where B_0 =0.61 is a constant, the value of which is fixed. The rate of change of drop radius in apparent parcel due to drop breakup is described by using the rate expression; $\frac{dr}{dt}=\frac{r-r_{new}}{\tau_{bu}},\tau_{bu}=3.788\frac{r}{\Lambda\Omega}$ (5) The spray –wall interaction model used in the simulations is based on the spray –wall impingement model descried in [8].The model assumes that a droplet, which hits the wall is affected by rebound or reflection based on the Weber number. The Dukowicz model was applied for treating he heat –up and evaporation of the droplet which is described in [11].This model assumes a uniform droplet temperature .I n addition the rate of droplet temperature change is determined by the heat balance which states that that heat convection from the gas to the droplet ether heat up the droplet or supplies heat for vaporization. With higher droplet densities and relative velocities droplet collisions occur. High droplet densities are restricted to the spray kernel. High relative velocities can especially be seen at the tip of the spray, where preceding droplets are decelerated by the gas. Depending on the droplet collision conditions various effects like elastic droplet bouncing, droplet coalescence and droplet atomization are observed. **4.2 Ignition and combustion models** The shell auto ignition model was used for modeling of the auto ignition [10].In this mechanism 6 species for hydrogen fuel, oxidizer, total radical pool, branching agent, intermediate species and products were involved. In addition the important stages of auto ignition such as initiation propagation, branching and termination were presented by generalized reactions described in [10]. The combustion model used in this study is of the turbulent mixing controlled verity as described by Magnusson and Heritage[11] .This model assumes that in premixed turbulent flames, the reactions (fuel ,oxygen) are contained in the same eddies and are separated from eddies containing hot combustion products . The chemical reactions usually have time scales that are very short compares to the characteristics of the turbulent transport processes .Thus it can be assumed that the rate of combustion is determined by the rate of intermixing on a molecular scale of the eddies containing reactants and those containing hot products in other words by the rate of dissipation of these eddies.

4.3 NOx and soot Formation Models

The reaction mechanism of NOx formation is expressed in terms of the extended a Zeldovich mechanism.N2+O↔ NO+N (6)N+O2 ↔ NO+O (7)N+OH ↔ NO+H (8)From the fact that in most stoichiometric and fuel –lean flames , the occurring OH concentration very small , the third reaction of the Zeldovich mechanism can be neglected .F or the formation of thermal Nox , the partial equilibrium approach can be used and the equilibrium of the first two reactions result in one global reaction as follows;

N2+O2↔2NO (9)

The chemical species appearing in this global reaction are used in the giver single –step fuel conversion equation via: $\frac{d[NO]}{dt}=2k_f[N_2IO_2]$= 2kf[N2/O2] (10)

Where only the forward reaction is considered and the reaction rate kf is given as

$$Kf=\frac{A}{\sqrt{T}}\exp\left(\frac{-E_a}{RT}\right) \qquad (11)$$

The soot formation model currently implemented in fluent is based upon a combination of suitably extended and adapted joint chemical /physical rate expressions for the representation of the processes of particle nucleation, surface growth and oxidation. $\frac{dm_{soot}}{dt} = \frac{dm_{form}}{dt} - \frac{dm_{oxid}}{dt}$ (12)

$$\frac{dm_{form}}{dt} = A_f m_{fv} p^{0.5} \exp\left(\frac{-E_a}{RT}\right) \quad (13)$$

$$\frac{dm_{soot}}{dt} = \frac{6M_c}{\rho_s d_s} m_s R_{tot} \quad (14)$$

4.4 Numerical model

The numerical method used in this study is a segregated solution algorithm with a finite volume –based technique. The segregated solution is chosen is due to the advantage over the alternative method of strong coupling between the velocities and pressure. This can help to avoid convergence problems and oscillations in pressure and velocity fields. This technique consists of an integration of the governing equations of mass, momentum species, energy and turbulence on the individual cells within the computational domain to construct algebraic equations for each unknown dependent variable. The pressure and velocity are coupled using the **SIMPLE** algorithm which causes a guess and correct procedure for the calculation of pressure on the staggered grid arrangement .It is more economical and stable compared to the other algorithms. The **upwind** scheme is always bounded and provides stability for the pressure correction equation. The CFD simulation convergence is judged upon the residuals of all governing equations. This scaled residual is defined as:

$$R^{\phi} = \frac{\sum_{cells} P \mid \sum_{nb} a_{nb}\phi_{nb} + b - a_p\phi_p \mid}{\sum_{cells} P \mid a_p\phi_p \mid}$$

Where Φp is a general variable at a cell p, a_p is the center coefficient, a_{nb} are the influence coefficients for the neighboring cells and b is the contribution of the constant part of the source term. The results reported in this paper are achieved when the residuals are smaller than 1.0×10 -4.

5.0 Turbulent dispersion of particles

Dispersion of particles due to turbulent fluctuations in the flow can be modeled using either **Stochastic tracking** (discrete random walk**) Particle cloud model** Turbulent dispersion is important because it is more realistic, enhances stability by smoothing source terms and eliminating local spikes in coupling to the gas phase.

Appendix

BTDC Bottom dead center

ATDC After top dead enter

CA Crank angle

SOI Start of injection

DOI Duration of injection

Table **1 Engine specifications**

Bore	**70mm**
Stroke	**78mm**
Displacement	**300mm**
Swirl ratio	**2.5**
Compression ratio	**19.5:1**
Injection angle	**150°, 70°**
Fuel injection system	**Common rail**

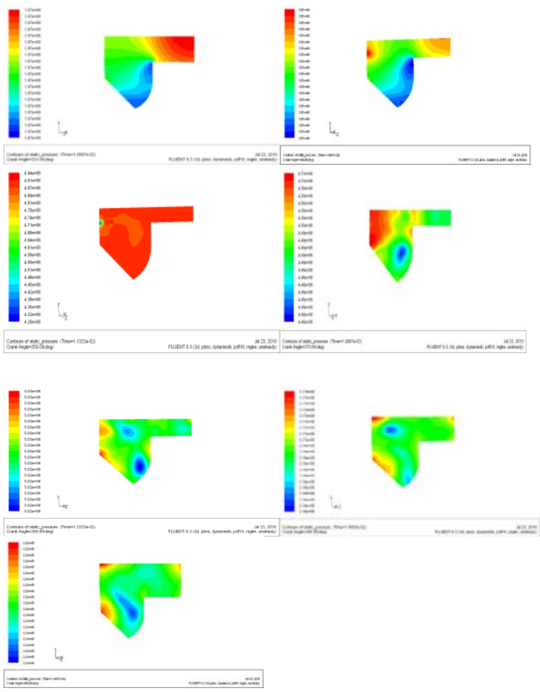
Table **2 Engine operating conditions**

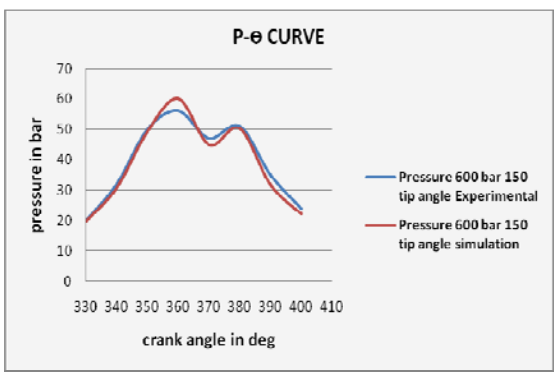
S.NO	**Injection angle(deg)**	**Injection pressure(bar)**
1	**150**	**600**
2	**150**	**1000**
3	**70**	**600**
4	**70**	**1000**

Table 3 **Properties of European diesel**

Specific gravity	**0.83**
Cetane Number	**52.9**
Sulphur,ppm	**27.5**
Boiling point (° c)	**260**

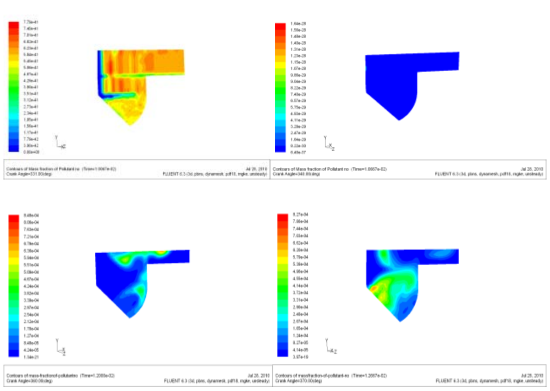
Results: Pressure contours

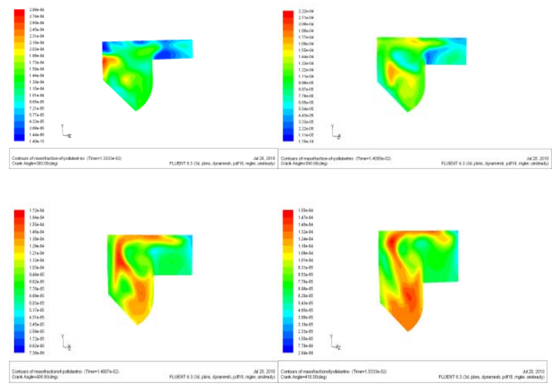


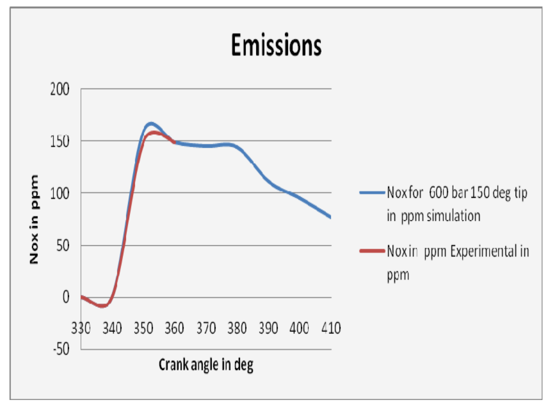


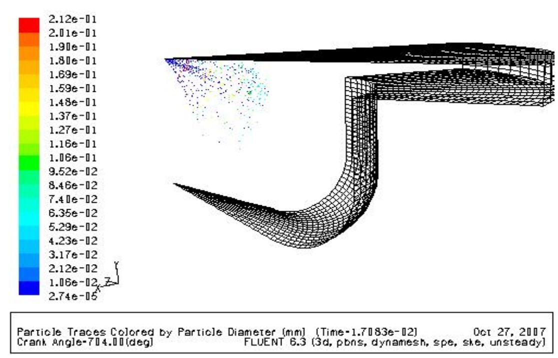
P-ɵ CURVE

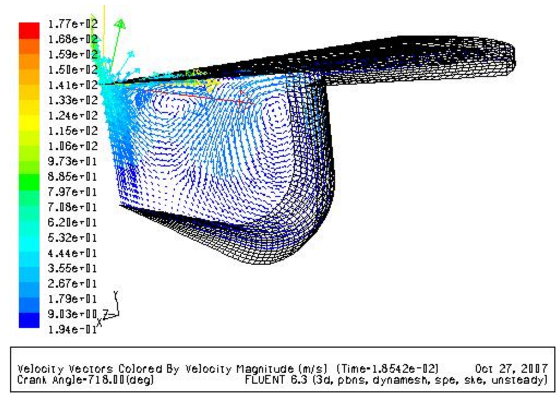
NOx contours 600 bar 150 deg

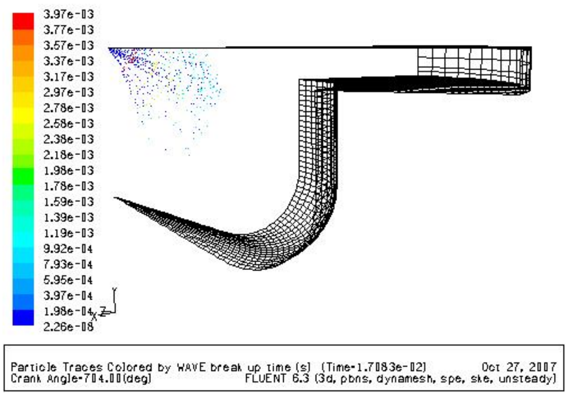












CONCLUSIONS

In this research work simulation has been carried out for injection angles on combustion process in a HSDI diesel engine employing multiple injections are presented. Premixed combustion has been observed for 150 degree tip with high injection pressure. P-ө Curve is almost similar to the Experimental results for both 150, 70 degree injection angles and for 1000,600 bar pressures. 70 deg injection angles with 600 bar pressure have shown less NOx. It would be understood that for medium pressures HCCI combustion taking place.

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