

Analysis of Diesel Engine In-Cylinder Air-Fuel Mixing with Homogeneity Factor: Combined Effects of Pilot Injection Strategies and Air Motion

Pavlos Dimitriou
University of Sussex

Weiji Wang
Univ of Sussex

Jun Peng
University of Hertfordshire

Li Cheng
University of Sussex

Matthias Wellers
AVL Powertrain Ltd

Bo Gao
AVL Powertrain UK Ltd

ABSTRACT

With a view to understanding the air-fuel mixing behavior and the effects of the mixture quality on the emissions formation and engine performance, a new quantitative factor of the in-cylinder air-fuel homogeneity named Homogeneity Factor (HF) has been developed. Its characteristics under various injection conditions and air swirl motions within the cylinder have been investigated with CFD simulation. The results have shown that air-fuel homogeneity is essentially affected by the spatial and temporal fuel distribution within the combustion chamber. Higher injection pressure, longer dwell time and increased pilot fuel quantities can contribute to better mixing quality resulting in increased HF and optimum engine performance with low fuel consumption and soot emissions. With regard to the in-cylinder air motion, increasing swirl ratio enhances the air-fuel mixing quality which has been reflected in the variation of the HF. As a result, increased in-cylinder pressure and temperature caused by the optimized air-fuel mixing improved the combustion efficiency.

CITATION: Dimitriou, P., Wang, W., Peng, J., Cheng, L. et al., "Analysis of Diesel Engine In-Cylinder Air-Fuel Mixing with Homogeneity Factor: Combined Effects of Pilot Injection Strategies and Air Motion," *SAE Int. J. Engines* 7(4):2014, doi:10.4271/2014-01-9052.

INTRODUCTION

Future diesel engines have to be cleaner, less expensive, provide higher power density and be more efficient to be competitive in the marketplace and be environmentally friendly. The combustion control is a key characteristic for economic, clean and powerful DI diesel engines. The combustion process can be controlled directly by the air-fuel mixing quality within the combustion chamber. The common rail (CR) technology has been fairly investigated and used in diesel engines over the last decades in automotive industry. In the late 1960's, the first CR prototype system was developed in Switzerland. However, the first successful application in a production vehicle

came a few decades later, in 1995, by DENSO Corporation which launched a newly developed CR system mounted on the Hino Rising Ranger truck [1]. CR injection system can provide multiple advanced injections per cycle within the cylinder at high injection pressures with flexible injection timing and volumes. The relatively new fuel injection technology has been primary used for reducing the noise level and exhaust emissions of diesel engine [2, 3, 4, 5]. Shuji et al. proved that CR advanced injection strategies could also lead to relative low combustion temperatures and be further beneficial for emissions reduction [6].

Extensive research has been carried out on the beneficial effects of multiple fuel injections within the cylinder chamber. The initial investigations carried out on the effects of pilot injection in the combustion process can trace back in 1995 with works from Pierpont et al. [7] and Minami et al [8] who demonstrated that by having a pilot injection in the combustion process, the ignition delay could be reduced and this led to a lower heat release rate, with less NO_x emissions and combustion noise. Mendez et al. [9] proved that combustion noise and instantaneous fuel burning rate could be decreased by splitting the heat release process as a result of multiple fuel injections per cycle. They also demonstrated that multiple injection strategies could be used for better control of the spatial fuel distribution and enhancing the air use in the combustion chamber. As a result, this could lead to a reduction in particulate emissions at intermediate engine loads. Montgomery et al. [10] showed that multiple injection strategies could reduce NO_x emissions by lowering the peak in-cylinder temperature when combined with exhaust gas recirculation (EGR) into the cylinder. However, the soot emissions were raised due to some increased temperature rich regions created as a result of the oxygen reduction in the cylinder. Park et al. [11] investigated the effects of multiple injections in a HSDI diesel engine equipped with CR injection system. They found that pilot injection reduces the ignition delay for the main injection and enhances the power output by controlling the intensity of premixed combustion. They also noted the importance of the post-injection in completing the oxidation process and reducing the particulate emissions even when small fuel quantities were injected. According to their results, multiple injection strategies could reduce particulate emissions by more than 40% in some cases.

Diez et al. [12] carried out an investigation in a single cylinder optical diesel engine for the effect of split main injection (30% to 70%) with short dwell angle (11.8o CA) and high EGR rates. The results showed improved indicated mean effective pressure (IMEP) and low NO_x emissions. However, owing to too short time between the two main injections the air-fuel mixing quality becomes poor, leading to high unburned hydrocarbon (uHC) and soot emissions. Tow et al. [13] showed the importance of the dwell angle between injections in order to control soot formation and suggested that there would be an optimal dwell angle at a particular operating condition. Mobasheri et al. [14] studied the effects of dwell between two injections and proved that for his testing operating conditions, the optimum dwell angle between the injection pulses was around 20oCA.

For the reduction of soot and NO_x simultaneously to meet future emissions legislation, CR technology can provide a constantly high injection pressure that improves the fuel atomization from the beginning to the end of the injection. Also, the high velocity of the fuel jet and the fuel droplets cause high turbulence energy and therefore reduces the need of swirl energy to reach a necessary mixture formation [15]. Badami et al. [16] studied the effect of fuel injection pressure. They achieved a reduction of particulate emissions up to 27% by

increasing the injection pressure from 1300 to 1500 bar in a HSDI diesel engine at 4000 rev/min. Their results also proved that particulate emissions can be reduced via enhanced spray penetration caused by the injection pressure increase. Agarwal et al. and Gumus et al [17-18] have also proved with their experiments that increasing the fuel injection pressure is effective for reducing the number concentration of particulates along with mass of particulates at all loads. Gumus et al. showed that increased injection pressure causes a decrease in smoke opacity, UHC, and CO, while it causes an increase in the emissions of CO₂, O₂ and NO_x. DENSO cooperation has recently developed and launched a new CR system with injection pressure up to 3,000 bar [19]. According to their research, the new system can increase fuel efficiency by up to 3 percent while also reducing particulate matter by up to 50 percent and NO_x by up to 8 percent compared to their previous generation system [19]. These changes allowed the fuel to atomize into finer droplets, which improved fuel ignition and combustion efficiency, resulting in increased fuel economy and cleaner exhaust emissions.

All the research work mentioned above clearly shows that the fuel injection strategy is crucial for improving the combustion process of diesel engines. However, for air-fuel mixing quality optimization, the in-cylinder air motion generated due to the design of the intake ports should be also taken into account. For instance, Karuppa and Manimaran [20] showed that by varying the swirl ratio from 1.4 to 4.1, the peak pressure, peak temperature and peak heat release rate increased by 7%, 8.6% and 31% respectively. Simultaneously, they proved that by increasing the swirl ratio from 1.4 to 4.1, peak soot level reduced by 30 % but peak NO_x emissions increased by 54 %.

In this paper, the Homogeneity Factor will be used for exploring the effects of pilot injection, fuel pressure, dwell angle etc. on the air-fuel mixing quality, engine performance and emissions formation. The paper is divided in the following categories; firstly the CFD model is validated compared to real engine test results. Then, simulations for six modes with different injection pressure and dwell time between pilot and main injection are performed for various pilot injections. Finally, simulation will be carried to examine the effect of all different swirl ratios to the air-fuel mixing homogeneity.

NUMERICAL METHOD

Sub-Models

Numerical simulations were conducted by using AVL FIRE CFD code for Diesel combustion. The submodels employed in the code have been chosen based on previous researchers' work and it has been suggested those sub-models are appropriate for high fuel pressure diesel combustion.

The atomization of fuel spray can be divided into two separate stages. The primary atomization takes place close to the nozzle and the secondary one occurs further away due to aerodynamic interactions. The WAVE and Taylor Analogy

Break-up (TAB) [21] models do not distinguish between the two processes. However, TAB model has not been used since it is not appropriate for cases with high injection pressures (greater than 40MPa) and predicts too small liquid and vapour penetrations. ETAB (Enhanced Taylor Analogy Break-up) [22], FIPA (Fractionnement Induit Par Acceleration) [23] or KH-RT (Kelvin Helmholtz-Rayleigh Taylor) [24], are some of the break-up models can be used for predicting the fuel spray atomization. However, these models treat and simulate the primary and secondary regions separately. This fact could cause a difficulty in estimating the correct values for the additional set of tuning parameters. In the code, the primary and secondary atomization of the fuel spray is predicted using the WAVE model [25], which has been widely used for high-speed fuel injections. The WAVE model assumes that the droplet size and the breaking up time is related to the fastest-growing Kelvin-Helmholtz instability [26]. The details of the newly-formed droplets are predicted using the wavelength and growth rate of this instability. The parameters of the model have been tuned to match the experimental data.

For the heat-up and evaporation prediction of the droplets, Dukowicz evaporation model [27] is selected for the simulations with diesel fuel. Dukowicz model determines the rate of droplet temperature change by the heat balance, which states that the temperature transferred from the gas to the droplet supplies heat for its vaporization. The model tunable constants have been adjusted to match the experimental data.

The k - ζ - f model recently developed by Hanjalic, Popovac and Hadziabdic (2004) [28] was used for the evaluation of the turbulence effect in the combustion chamber. The k - ζ - f model is widely used in IC flows due to its robustness to be used for computations involving grids with moving boundaries and highly compressed flows. Moreover, for IC flows, the k - ζ - f model leads to more accurate results compared to the standard much simpler two equation k - ε [29] and RNG k - ε [30] models.

ECFM-3Z (Extended Coherent Flame Model - 3 Zones) model [31] was applied for the combustion model of the simulations. ECFM-3Z separates a computational cell in 3 zones in order to enable specific treatment for air fuel mixing, auto ignition, combustion and pollution formation processes. The three different regimes computation aids to a deep understanding of the turbulence flow and provides data inaccessible with experimental devices such as fuel mixture fraction distribution and fuel evaporation rate.

Finally, Zeldovich [32] and the Kennedy, Hiroyasu and Magnussen mechanism [33] were implemented in the software for NO_x and soot formation respectively. The soot formation implemented is based upon a combination of suitable extended and adapted joint chemical/physical rate expressions for the representation of the processes of particle nucleation, surface growth and oxidation.

The list of all the sub-models have been implemented is presented in [Table 1](#).

Table 1. Computational submodels

Break-up model	WAVE model [25]
Evaporation model	Dukowicz [27]
Turbulent model	k - ζ - f model [28]
Combustion model	ECFM-3Z model [31]
NO _x mechanism	Extended Zeldovich [32]
Soot model	Kennedy, Hiroyasu and Magnussen [33]

Engine Specifications

A light duty diesel engine with compression ratio of 18.3:1 and swept volume of 0.5 litre (per cylinder) is used in this study. A six-hole injector is placed centrally in the test engine to spray the fuel in the combustion chamber. The specifications for the engine and injection system are listed in [Table 2](#) and [Table 3](#).

Table 2. Engine specifications.

Displaced volume	0.5 litre
Stroke	86 mm
Bore	86 mm
Connecting rod	143.5 mm
Compression ratio	18.3:1
Number of valves	4
Inlet Valve Close	64° ABDC
Exhaust Valve Open	69° BBDC
Engine speed	2000rpm
Piston shape	Mexican hat style

Table 3. Fuel injection characteristics.

Injection pressure	800 to 1600 bar
Number of nozzle holes	6
Nozzle hole diameter	0.169 mm
Fuel type	49.1 CN diesel

Computational Grid

The piston and the injector geometry parameters have been set in the software using the 2D Sketcher tool. The computational grid was generated and the model tested under various mesh sizes in order to make sure that the results are grid independent. The grid independence analysis is presented in [Figure 1](#).

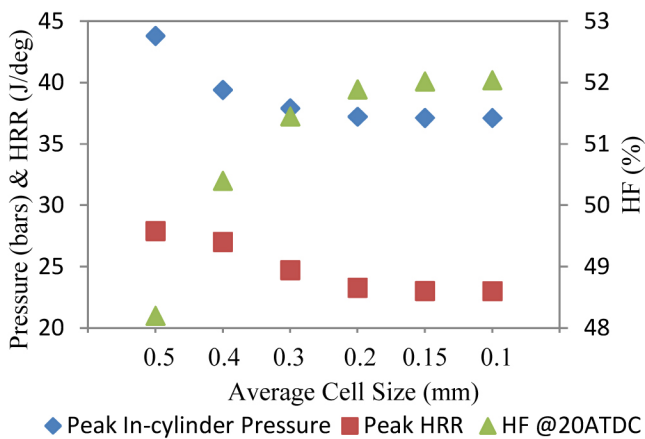


Figure 1. Computational Grid Independence Analysis.

The final grid independent model, shown in Figure 2, has an average cell size of 0.15mm with relatively denser meshing existing closer to the injection tip and the TDC clearance gap. The model consists of 42,052 and 72,052 hexahedral cells at TDC and BDC respectively.

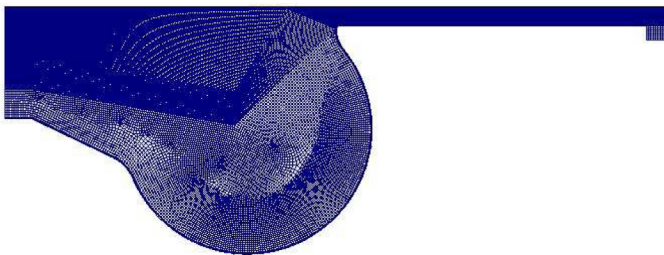


Figure 2. Computational grids at TDC.

Test Conditions

The tests were performed under the following air and fuel conditions. The simulation is carried out on a 60° sector for reduced calculation time due to the symmetric location of the 6-hole injector at the centre of the combustion chamber. Calculation starts at the inlet valve closure (IVC) and ends just before the exhaust valve opening (EVO) for time saving reasons.

Table 4 specifies the air and fuel initial conditions for all the simulations.

Table 4. Initial air & fuel conditions.

Intake air temperature	380 K
Intake air pressure	1 bar
Fuel temperature	350 K
Fuel injected	13.98 mg/cycle
Number of injections	2
Total injection duration	14.6 ° to 20.6° CA
Start of Pilot Injection	19.12° to 5.73° CA BTDC
Start of Main Injection	TDC

Tests were divided into two main categories. The first category involves the study of six different modes with variation of the injection pressure and dwell angle between the injections. The six modes defined below in table 5 were simulated for three different pilot injection quantities of 0.7, 1.4 and 2.8 mg/cycle.

Table 5. Engine test conditions.

Mode	Inj. Pressure (bar)	Dwell Angle (CAD)
1	800	5
2	1200	5
3	1600	5
4	800	15
5	1200	15
6	1600	15

The second set of tests performed analyzes the swirl effect on the air-fuel mixing quality and emissions of the engine. The 6 modes defined earlier were compared for three different swirl ratios of 1.5, 2 and 2.5.

PARAMETER DEFINITION

In this paper, the mixing quality parameter used is one named Homogeneity Factor (HF) which was originally developed by Peng and Liu [34]. The air-fuel mixing quality is measured based on the fuel difference in a calculated cell (e.g. Cell i), compared to the average equivalence ratio:

$$\frac{\Phi_i}{AFR_{st} + \Phi_i} \delta m_i - \frac{\Phi_0}{AFR_{st} + \Phi_0} \delta m_i = \frac{(\Phi_i - \Phi_0) AFR_{st}}{(AFR_{st} + \Phi_i)(AFR_{st} + \Phi_0)} \delta m_i$$

where AFR_{st} is the stoichiometric air-fuel ratio, Φ_i is the equivalence ratio in cell i, Φ_0 is the average equivalence ratio and δm_i is the mass of the mixture in the computational cell i.

The Total fuel amount in the cylinder is,

$$\frac{\Phi_0}{AFR_{st} + \Phi_0} M$$

Then, a parameter named Heterogeneity Factor (HeterF) can be expressed as,

$$HeterF(\theta) = \sum_{i=1}^{N_{cells}} \frac{\sqrt{(\Phi_i - \Phi_0)^2} \delta m_i}{2\Phi_0 M \left(1 + \frac{\Phi_i}{AFR_{st}}\right)}$$

As the increased fuel amount in a cell actually comes from the decrease of fuel amount in other cells, the half of the standard deviation is used in the definition to reflect the non-uniformity more accurately.

Based on HeterF, the homogeneity factor (HF) can be derived for having a quantitative demonstration to the charge mixing quality.

$$HF(\theta) = (1 - HeterF(\theta))\%$$

Compared to Nandha and Abraham's definition for Degree of Heterogeneity (DOH) which actually represents the standard deviation of the equivalence ratio normalized by the overall equivalence ratio [35], the HeterF (heterogeneity factor) is the standard deviation of fuel amount normalized by the overall fuel amount. This will be a more reasonable measure to the non-uniformity in the mixture.

MODEL VALIDATION

The CFD model was validated using experimental data conducted on the single cylinder research engine with the specifications as listed in Table 2.

Figure 3 and Figure 4 show the comparison between the predicted and measured in-cylinder pressure and heat release rate for low load at 1,200rpm and high load at 2,000 respectively. The result is based on the assumption of uniform wall temperature 470 K for the cylinder wall and 570 K for the cylinder head and the piston top.

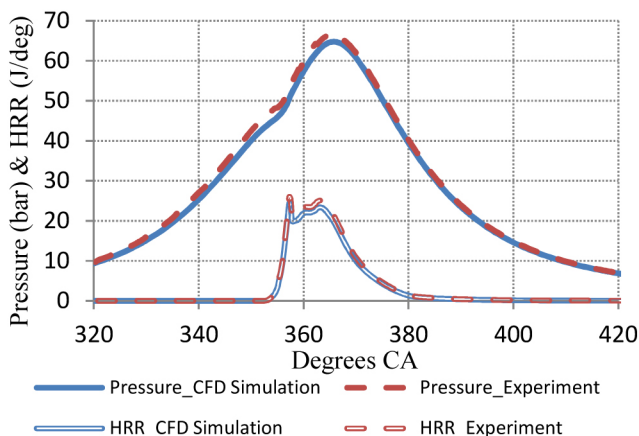


Figure 3. Comparison of simulated and measured in-cylinder pressures and heat release rates for single injection at 1,200rpm, low load.

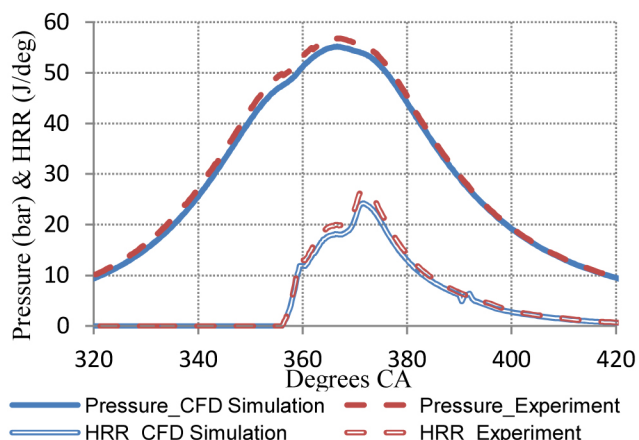


Figure 4. Comparison of simulated and measured in-cylinder pressures and heat release rates for single injection at 2,000rpm, high load.

The CFD simulation trend for the in-cylinder pressure seems to be in reasonable agreement with the experimental measured values for both operating conditions. There is only a slight pressure difference after the start of combustion which might be related to experimental uncertainties in input parameters to the computations such as the precise injection duration, start of injection and gas temperature at the IVC. On the other hand, the calculated heat release rate based on the experimental results seems to follow the same trend as in the simulation. However, the calculated HRR is slightly higher than the simulation experiments and it seems to have a smoother drop after the end of combustion. It is considered that the slight pressure and HRR variations between the experimental and simulation results will have a minimum impact on the results of the in-cylinder mixture homogeneity. A contingent small fuel injection variation will not significantly interfere with the air and fuel flow motions within the cylinder.

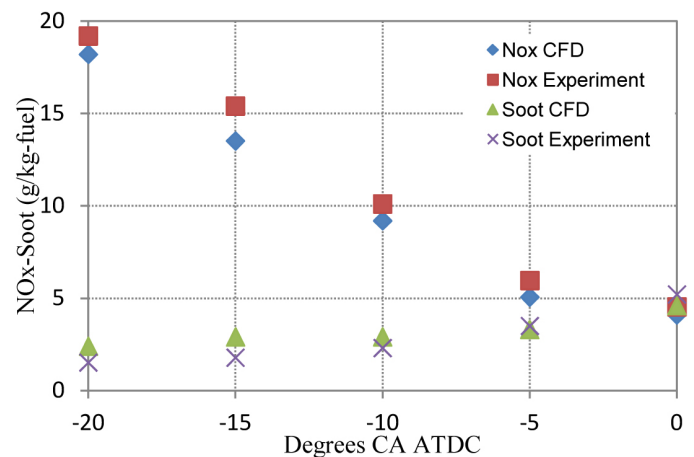


Figure 5. Comparison of simulated and measured NOx and soot emissions for single injection.

Figure 5 presents the comparison of NOx and soot emissions formation for single injection cases with different start of injection timings at 2000rpm. It can be seen that simulation and experimental emission result are nearly matching for the cases where the start of injection occurs close to TDC. For cases with an earlier start of injection, there is a very slight divergence which has possibly been caused by some air motion instabilities.

Figure 6 shows the NOx and soot results gathered for three operating conditions featuring a pilot injection at an injection pressure of 1,600bar and a dwell angle of 5° CA. It can be noticed that the simulation and experimental results for operating conditions featuring pilot injection are not as identical as the results of the single injection cases. This could possibly happen due to variations of the injected fuel mass compared to the simulation model. Injection mass variations can be caused by fuel dribbling after the pilot injection or by failure of the injector's needle to reach its maximum lift due to the very small fuel amount injected during the first pulse. This can be also confirmed by the higher error in the soot and NOx emissions for the cases with very low pilot fuel amount.