An Interpretation of High Swirl Diesel Combustion Based on Optical Diagnostics and 3D Numerical Calculations

Massimo Astarita*, Felice E. Corcione*, Alessandro De Maio**, Bianca M. Vaglio*, Gerardo Valentino*

*Istituto Motori-CNR, Via G. Marconi, 8
80125 Napoli, Italy
**IAC-CNR
Roma
Italy

ABSTRACT

A phenomenological description of mixture formation and first stage of combustion occurring in a small high swirl combustion chamber of a diesel engine has been derived from measurements of spectral absorption and flame emissivity, and 3D calculations made with KIVA-3 code. Measurements have been carried out in an optically accessed combustion chamber in which an air swirling flow is forced from the main chamber through a tangential passage. A conventional injection system was used to inject tetradecane. The distribution of liquid and vapor and the interaction with air swirl have been detected by combined use of light absorption in the range from UV to Visible and laser doppler velocimetry (LDV). Spectral chemiluminescence measurements within the chamber have allowed to determine the spatial locations of OH at time of combustion. The interaction between the evaporating spray and the swirling air flow has been studied by using KIVA-3 with a $k-\varepsilon$ turbulence model and different spray submodels.

INTRODUCTION

Divided swirl chamber combustion systems are well suited to small high-speed diesel engines, mainly installed in passenger cars. The engine performances and the exhaust emissions are strongly influenced by the complex interaction between the fluid dynamic field, the spray breakup and droplets evaporation.

The recent advances of the optical diagnostic techniques and multidimensional models of internal combustion process can considerably improve the knowledge of these phenomena and figure out a conceptual model of the mixture formation and of the first stage of combustion.

Laser sheet imaging diagnostics like Rayleigh and Mie-scattering imaging [1-3], fluorescence technique [4] and ultraviolet (UV) to visible absorption measurements [5,6] and laser induced incandescence [7], have permitted to follow the combustion phenomena in terms of liquid and vapor distribution, soot particle size and number density and some species concentration. Moreover, the increase of computer power has allowed engineers to include more details, in terms of fundamental physics, into their engine simulations, while still being able to perform the desired calculations in an acceptable turn-around time [8]. In the 1989, Pinchon [9] made calculations of fluid mechanics and combustion in a prechamber diesel engine using a customized version of KIVA code. The conclusion was encouraging because the calculations were in fair agreement with experimental results. Corcione et al. [10] showed that the KIVA calculations can interpret accurately the fluid dynamics of internal combustion engines using experimental data for validation. Reitz et al. [11] and Corcione et al. [12] showed that new breakup models, droplet drag and droplet vaporization can improve the prediction capability of the KIVA code in terms of mixture formation and combustion.

The aim of the present paper is to analyze, in a high swirl diesel prechamber, the fluid mechanics by LDV, the mixture formation and the first stage of combustion by UV-Visible absorption and flame emissivity. Experimental results have been compared to KIVA-3 calculations.

EXPERIMENTAL APPARATUS

Divided-Chamber Diesel System

A four-stroke, water cooled, single cylinder diesel engine (10 cm bore and 9.5 cm stroke), having a displacement of 750 cm$^3$ was used. The engine was modified realizing an external combustion chamber connected to the main chamber by a tangential passage with large optical accesses. The standard piston having a toroidal bowl was replaced with a flat one and the chamber was set external to the top of the engine. A compression ratio of 22.3 :1 was set to compensate the increased heat losses. The external chamber had the piston-bowl volume of 21.3 cm$^3$ with three optical accesses: two in the longitudinal direction and one in that orthogonal. Moreover, a single hole nozzle, with a diameter of 0.027 cm, was located centrally on the top of the divided chamber; it was electronically controlled to set a fixed number of combustion shots.

Measurements of diesel combustion were performed using tetradecane fuel. Measurements of indicated pressure, under motored and firing conditions, within the prechamber and the main chamber, were detected at 2,000 rpm. Details and specifications of the engine are reported in Table 1. The time history of the injection and combustion pressure, the
needle lift and the rate of heat release at 2,000 rpm, is shown in Fig. 1.

<table>
<thead>
<tr>
<th>Engine type</th>
<th>Diesel, 4 stroke</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bore</td>
<td>10.0 cm</td>
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<tr>
<td>Stroke</td>
<td>9.5 cm</td>
</tr>
<tr>
<td>Single hole nozzle</td>
<td>0.027 cm</td>
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<tr>
<td>Displacement</td>
<td>750 cm³</td>
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<td>Connecting rod length</td>
<td>17 cm</td>
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<tr>
<td>Divided-chamber volume</td>
<td>21.3 cm³</td>
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<tr>
<td>Swirl ratio</td>
<td>90</td>
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<td>Connecting duct diameter</td>
<td>0.8 cm</td>
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<tr>
<td>Clearance height at TDC</td>
<td>0.15 cm</td>
</tr>
<tr>
<td>Volumetric compression ratio</td>
<td>22:3:1</td>
</tr>
<tr>
<td>Injected fuel per stroke</td>
<td>0.0091 g</td>
</tr>
<tr>
<td>Fuel</td>
<td>Tetradeacane</td>
</tr>
<tr>
<td>Start of injection (SOI)</td>
<td>8° BTDC</td>
</tr>
<tr>
<td>End of injection (EOI)</td>
<td>9° ATDC</td>
</tr>
<tr>
<td>Pressure start of comb. (PSOC)</td>
<td>5.8° BTDC</td>
</tr>
</tbody>
</table>

Table 1 - Engine specifications.

The fuel is injected by an injection system into the swirling flow. The injection starts 8° BTDC (before the top dead center), with a duration of 17° about TDC. The time of ignition has been defined as the first minimum in the heat release curve at the onset of the premixed combustion (5.8° BTDC). This crank angle, called pressure start of combustion (PSOC) is different from the luminous start of combustion (LSOC) that is the time of the first appearance of luminous flame due to soot radiance. The rate of heat release shows a small peak of premixed combustion, with a diffusive one due to the remaining of fuel injected at the end of premixed combustion.

Optical Apparatus

Polychromatic flame intensity and extinction measurements from UV-Visible were performed by the experimental setup shown in Fig. 2. In particular, in order to carry out polychromatic extinction measurements, a high pressure Xenon flash lamp with its broad band emission spectrum and the high emission intensity reached in the 200-350 nm range was used.

The light pulses had a short rise time of 5 μs and a duration of 1.2 ms. The silica lens L1 (f=160 mm) focused the light beam on the control volume inside the combustion chamber. The flame intensity and the extinct signals were collected and focused with a fused silica lens L2 (f=100 mm) on the entrance slit of a 32 cm focal length luminous spectrograph, with a groove blazed at λ=300 nm. The spectral image formed on the polychromator exit plane was detected on a gated image intensifier coupled with a CCD camera with a resolution of 512x512 pixels. The high spatial resolution of the CCD camera allowed the detection of 7 items (resolution 0.1x1mm²) about each location simultaneously. Thus, the total measure points in the combustion chamber were 119 for 17 locations. The synchronization of the image intensifier, the CCD camera, and fuel injection was driven by the shaft encoder signal through a unit delay.

The absorption and emission spectra of radicals such as OH and HCO in the range 200-350 nm were detected with the same optical apparatus using a narrow UV filter to avoid stray light effects due to visible light. The concentration of these species were evaluated from the spectra by the peak height determination subtracting the flame emissivity background signal.

The UV-visible absorption measurement allows to characterize vapor and liquid phase of fuel because the absorption band of the liquid compounds are present in this range. In particular, the liquid phase shows a broad spectrum with high intensity in the UV and a flat profile in the visible range, on the other side the vapor phase shows a peak only in the UV [5,6].

The Laser Doppler Velocimetry (LDV) system, Fig. 2, comprises an Argon-ion laser that utilizes the two lines at 488 and 514.5 nm, modular optics working in backscatter mode, two photomultipliers, and two burst spectrum analyzers (BSA). The system can extract Doppler frequencies from bursts with a very poor signal to noise ratio, and provides a high data rate up to high engine speeds with more than 90% of validated data. The optical shaft encoder, with a resolution of 0.2°/CA, drives a trigger device to enable the two burst spectrum analyzers.

Data were sent to a PC, via a IEEE488 parallel interface, and analyzed off-line by using an ensemble averaging procedure to estimate the mean motion [10]. LDV tests of the instantaneous tangential velocity were performed at different locations along the compression stroke and results will be provided at 10° BTDC and TDC. To minimize the statistical uncertainty of the results, the measurements were ensemble averaged on 250 consecutive combustion cycles.
NUMERICAL SIMULATION

The computations were carried out by using a modified version of KIVA-3 code, developed by A.A. Amsden [13] for numerical calculation of transient, two- and three-dimensional chemically reactive fluid flows with sprays. KIVA-3, which is an extension of the earlier KIVA II, uses the same numerical solution procedure and solves the same set of equations. KIVA-3 differs from KIVA II because it uses a block structured mesh with connectivity defined through indirect addressing. It allows to model complex geometries like the high swirl combustion system used in the present investigation. However, KIVA-3 can be fully exploited only using an external mesh generator.

In the present study, the computational mesh was obtained by the CAD package ENGAGE-IBM. It is a semi-automatic block-structured mesh generator based on the industrial Computer Aided Design CATIA® by Dessault Systems. Starting from a CAD model of the geometry, ENGAGE allows the user to build an optimized mesh compatible with KIVA-3. A picture of the engine meshed by ENGAGE is reported in Fig. 3.

In order to match, with a good accuracy, the compression ratio and the indicated pressure the grid has been drawn as uniform as possible according to the shape of the chamber and to the tangential duct connecting the swirl chamber to the main chamber. Further, the grid size has been chosen as a compromise between accuracy and run time also checking the agreement between the computed and measured indicated pressure within the engine prechamber at 2,000 rpm under motored conditions.

Runs were performed using the standard $k-\varepsilon$ turbulence model whereas the spray models have been improved by using the standard TAB model [14], the wave breakup model by Reitz et al. [11], and the DDB model proposed by Ibrahim [15] and validated by Corcione et al. [12]. All spray models have been further modified to account for spray-wall impingement effects. Finally, the droplet vaporization model by Spalding [16] has been used. The initial conditions of air flow and fuel rates were set according to experiments.

RESULTS AND DISCUSSION

The results discussed in the present paper should be a contribution to draw a conceptual description of the mixture formation and the first stage of combustion, occurring in a small high speed IDI diesel engine, based on the application of advanced optical techniques and multidimensional models to the engine. The work of Dec and co-workers [17], made on an optical access version of a heavy duty diesel engine, is an example of using an array of advanced diagnostics to obtain details of the spray and combustion processes. However, the engine used in the experiments of Dec has a quiescent
combustion system, so the conclusions cannot refer to small high swirl engines like that used in the present investigation.

**Fluid Mechanics**

The nature of the air motion within the combustion volume has been analyzed by LDV and KIVA-3. Figure 4 shows the computation of the velocity distribution obtained, on the middle plane of the prechamber, at 10° BTDC and at TDC, respectively. It can be noted that the tangential passage, connecting the main chamber to the swirl chamber, induces a strong air vortex during the compression stroke. The vortex assumes the characteristic shape of a non-centered rotating solid body at 10° BTDC and becomes almost centered to the chamber axis at TDC.

120 to 150 m/s. A worse agreement is noted at the exit of the tangential duct due to the strong instability of the flow generated by the tangential passage that induces in the chamber very high velocity gradients. To overcome this discrepancy, the size of computational grid, set at 1.3x1.3x1.2 mm³ in the present investigation, should be strongly reduced. However, this would increase the run time that is already of 36 hours on an IBM-SP2 UNIX machine for only compression stroke from BDC (bottom dead center) to TDC.

**Figure 4.** Computed air velocity distribution at 10° BTDC (top plot) and TDC (bottom plot).

**Figure 5.** Comparison of air tangential component between LDV (left plots) and KIVA (right plots).

**Mixture Formation**

The absorption measurements in the range from UV to visible have allowed to draw a temporal sequence of schematic images of liquid and vapor phases from the start of injection to the first appearance of OH radicals. Fig. 6 shows the comparison between experiments and calculations of the liquid and vapor distributions, averaged along the line of sight, at 1, 2, and 4 crank angle degrees ASOI (after the start of injection), respectively. Plots of the liquid and vapor concentration, estimated by absorption measurements, are normalized with respect to the maximum and reported in dimensionless arbitrary units in the range from 0 to 1.

It can be observed, at 1° ASOI, that the dark region containing only liquid fuel is located on the top of the chamber. The strong anti-clockwise swirl distorts the jet towards the chamber wall and forces hot air in the jet contributing to vaporize the fuel. A vapor region develops at 2° ASOI, it expands along the sides of the jet as shown by the vapor isocontours. The tip penetration increases and the vapor, transported by the swirl, starts to fill the chamber (4° ASOI). The vapor distributes along the wall of the chamber because of the effect of the strong swirl motion. The temporal sequence of schematic images, observed in Fig. 6, computed by KIVA-3 with standard k-ε turbulence model and WAVE breakup spray model, shows a fair agreement with the experimental estimate. The agreement between the shape of liquid spray is not good due to the intrinsic limitation of the
representation of the computational results that gives the fuel droplets distribution while the experiments show the liquid concentration in gray levels.

Fair agreement between the pattern of computed and experimental vapor isocontours is observed. Calculations in Fig. 6 also show that the vapor concentration increases along the chamber wall and expands towards the inlet duct transported by the rotating air flow where it assumes the lowest levels due to the dilution effect of the fresh air coming from the tangential duct. However, the computation can give more information about the spatial distributions of vapor concentration and temperature allowing to understand why radicals appear in a region rather than other ones.

1° ASOI

2° ASOI

4° ASOI

Figure 6. Comparison between calculations (left plots) and experiments (right plots) of liquid and vapor distribution averaged along the line of sight.

Looking at Fig. 7, that reports the air temperature map, it can be noted that the region with lowest values is located along the chamber wall where vapor subtracts heat from the fluid. The last schematic images, Fig. 8, show the isocontours of OH radicals, obtained processing the chemiluminescence measurements in the UV range, at 2.2° and 2.8° ASOI, respectively.

Figure 7. Computed temperature distribution (°K) at 4° ASOI.

OH is detected in the richest region of vapor-air mixture located in front of the jet. The first appearance of OH is at 2.2° ASOI corresponding to the minimum of heat release curve of Fig. 1. This means that the combustion starts with a chemical activity that produces radicals and an increase of temperature and pressure.

Figure 8. OH concentration at 2.2° (left plot) and 2.8° (right plot) ASOI.

Summarizing the results, an interpretation of the first stage of combustion can be drawn. After a physical ignition lag that allows the jet penetration, drop break up, and vaporization, an energetic chemical activity arises in the richest region in front of the tip of the spray. Moreover, the first appearance of OH falls 2.2° ASOI corresponding to the minimum of heat release curve. This scheme of the first stage of combustion is different from what was thought before the use of modern optical techniques when the first appearance of soot was considered as the start of premixed combustion [18].

CONCLUSIONS

A phenomenological interpretation of mixture formation and first stage of combustion occurring in a small high swirl combustion chamber of a diesel engine has been derived from LDV, spectral absorption and chemiluminescence measurements, and 3D calculations made
with KIVA-3 code. Measurements have been carried out in an optically accessed high swirl combustion prechamber in which tetradecane was injected.

The main results can be summarized as follows:

1. Good agreement between LDV measurements and KIVA predictions has been obtained. The tangential passage connecting the main chamber to the swirl chamber induces a strong air vortex during the compression stroke. The vortex assumes the characteristic shape of a non-centered rotating solid body at 10° BTDC and becomes almost centered to the chamber axis at TDC.

2. The pattern of computed and experimental isocontours of vapor concentration are in fair agreement. It indicates that the vapor concentration increases along the chamber wall and expands towards the tangential passage transported by the rotating air flow where it assumes the lowest levels due to the dilution effect of the fresh air coming from the tangential duct.

3. An OH region is detected where the vapor-air mixture is richer and it appears at the crank angle of minimum of heat release curve suggesting a conceptual scheme of the first stage of combustion different from what was thought before the use of modern optical techniques.

REFERENCES


