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Experimental and Numerical Characterization of the Fuel Distribution by a GDI Multi-Hole Injector for Spark Ignition Engines

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Abstract

The capability of the new generation gasoline multi-hole injectors to operate in the so-called jet-guided combustion mode allows an accurate control of the fuel distribution in the engine combustion chamber, adequate to the whole range of engine operating conditions.

In this paper an experimental and numerical investigation of the spatial-temporal distribution of gasoline issuing from a six-hole injector with a hollow-ellipsoid footprint structure is presented. Commercial gasoline is delivered at different injection pressures and several total mass in an optically-accessible vessel at controlled conditions of the gas pressure and ambient temperature. Images of the spray, lightened by high intensity flashes, are collected at different instants from the start of the injection by a synchronized high-spatial resolution CCD camera. The captured frames are processed off-line using a professional dedicated software to extract the main parameters characterizing the spray evolution. The fuel injection rates are also measured by a fuel injection rate meter operating on the Bosch tube principle.

The numerical simulation is performed by means of the AVL Fire™ code. A first set of computations is effected in order to reproduce the actual experiment, by considering the evolution of the gasoline spray in a controlled environment. Measured injection flow rates and cone angles are used as input variables. Comparison between the achieved numerical results and the experimentally evaluated penetration length allows the establishment of a break-up model and initial droplet size distribution better approximating the experiment.

In a second part of the paper the assessed model is employed to simulate the mixture formation process in a high speed four-stroke spark ignition engine, exhibiting a pent-roof cylinder head and four valves per cylinder. Different positions of the injector are considered within the constructive constraints.

Introduction

Gasoline Direct Injection (GDI), in Spark Ignition (SI) engines, nowadays appears as the most promising way to achieve the two objectives of lowering fuel consumption and maximizing performance. Compared to the conventional Port Fuel Injection (PFI), it allows the combustion to proceed stably for a wide interval of global air-to-fuel ratios, namely not only under stoichiometric or rich conditions of the air-fuel mixture, but also in an ultra-lean mode, where charge stratification is exploited. In other words, the homogeneous mixture needed for moderate and heavy loads, is substituted, at the lightest loads, by a charge exhibiting a high fuel concentration around the spark plug and air rich zones close to the wall, which also help in reducing pollutants formation and the tendency to detonate. The possibility of improving the combustion process development over an extended range of operating conditions requires tools able to predict, with a good accuracy, the engine behavior under different mixture formation modes. In principle, Computational Fluid dynamics (CFD) may be adapted to the task, although, in the practice, the choice of the physical models and the validation of the employed codes are not always so simple and straightforward to lead to the desired predictability. Particularly, it appears the spatial-temporal dynamics of sprays due to the lack of detailed experimental data which may serve as input data for the simulation or to tune constants involved in the employed models.

The present paper presents an example of assessment of a numerical code for the prediction of the mixture formation process in a GDI SI engine. The work exploits the results of an experimental campaign conducted on a new generation six-hole injector. This, with its hollow-ellipsoid footprint structure, may be employed in the so-called air-guided and in the jet-guided combustion mode since it achieves a strong atomization of the injected fuel. Information about the more correct injector position and orientation in the engine combustion chamber is strongly demanded in order to assure a flexible charge stratification adequate to the whole range of operating conditions. The developed

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model is first calibrated based on an experimental characterizing the structure of the spray in terms of droplets atomization and dispersion. Preliminary results of the simulation of the intake, compression and expansion stroke of the considered pent-roof head 4-valve single cylinder engine are reported.

Experimental Apparatus and Procedures

Commercial gasoline (ρ=740 kg/m^3) is delivered through an hydro-pneumatic injection system and a Bosch six-hole GDI injector without a rotating pump. A compressed gas, ranging from 0.07 MPa to 0.7 MPa in input at the injection system, produces an output pressure of the fuel changing linearly from 2.5 to 25 MPa. In Figure 1 a schematic of the injector lay-out is shown. A reservoir tank of 1.0 dm^3, located before the electro-injector (1), assures the absorption of the pressure oscillations produced from the needle opening and the gas recharge. Piezoresistive and piezoquartz pressure transducers, located on the pump-reservoir pipeline and on the injector connection (2), respectively, allow the monitoring of the injection pressure and the fuel delivered oscillations. The injector is housed in a pressure holder (3), connecting the pump to the accumulator, and is used for spraying the fuel (4). It is driven by a Programmable Electronic Control Unit (PECU) operating in the multinjection mode, with the opening time related to the energizing current duration. Further details of the apparatus are reported in ref.[1].

Measurements of the fuel injection rate are carried out for the adopted strategies by means of an AVL Meter operating on the Bosch principle [2, 3]. Injection pressures of 10 and 20.0 MPa are explored with delivered quantities of 20 and 50 mg/str. A sketch of a solenoid energizing current duration of 2.6 ms and the corresponding fuel injection rate from the AVL meter at 20.0 MPa injection pressure are reported in Figure 2. The system injects 50.88 mg/str, while the delay from the current start and the first appearance of the gasoline from the nozzle is 400 μs.

The characterization of the spray development is achieved in an optically accessible high pressure quiescent vessel. The gas backpressures are set at 0.05 and 0.1 MPa. The jets, emerging from the nozzle, are lightened by powerful flashes at different instant from the Start Of Injection (SOI). A synchronized high resolution CCD camera, 0.5 μs shutter time, 12 bit, captures the images. The alignment of the jet direction, with respect to the camera axis is permitted by a wet seal spherical holder enabling the injector to tilt in the angular range of +/- 15°.

The images of the spray are collected by the CCD with optical axes in both parallel (set-up A) and orthogonal (set-up B) conditions with respect to the spray propagation. A set of 5 images are captured for each injection condition for a statistical analysis and in order to account for cycle-to-cycle dispersion.

The tip penetration and the spray-cone angle are measured to characterize the performance of the spray at fixed conditions. The main hypothesis is that the six jets all behave in a similar way, so that measurements may be carried out on a single jet only. This condition could not be true for time greater than 1.0 ms, when the jets' swelling produces a non-negligible interaction between the jets which influences both droplets penetration and sizing. The images processing analysis is carried out by means of dedicated professional software taking into account background subtraction, filtering and edges determination for tip penetration and cone angle measurements. Details can be found in ref. [1].

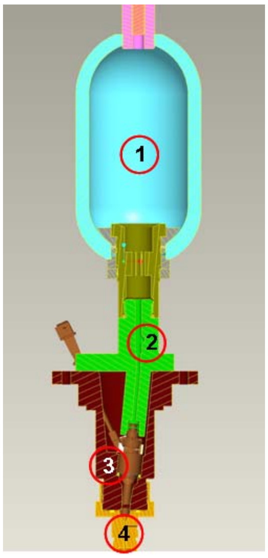

Figure 1. Schematic of injector layout

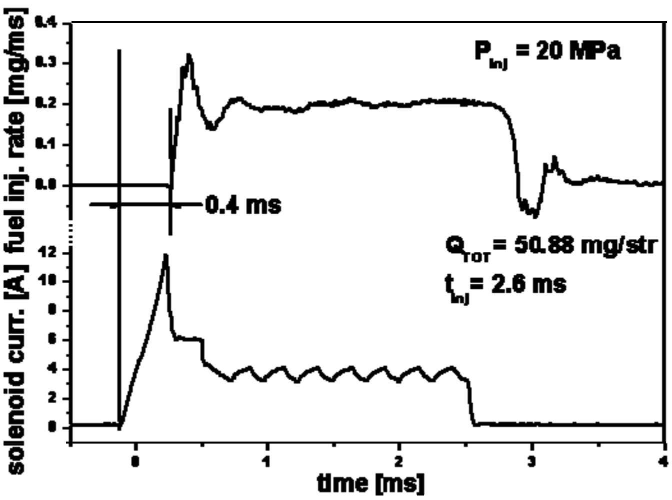

Figure 2. Solenoid energizing current and fuel injection rate

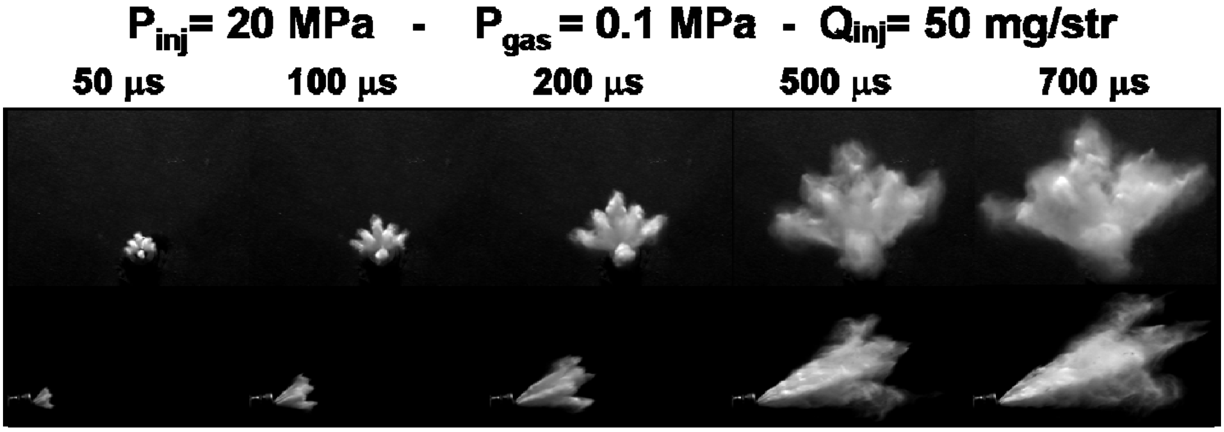

Figure 3. Spray evolution sequences at the indicated conditions taken by the set-up A (top) and B (bottom)

Results

A sequence of images of the jets evolution is reported in Figure 3. The pictures, taken for the 20.0 MPa injection pressure, 50 mg/str injected quantity and atmospheric backpressure in the vessel, are captured using the A and B set-ups. The frontal view of the spray highlights the jet plumes and their independent evolution up to about 200 μs from the SOI. The jets propagation is clear and gives an indication of the fuel distribution inside the vessel. This regularity appears destroyed for the 500 and 700 μs images where the interference between the single jets appears evident and the single jet evolution can not be longer followed. Here the fuel has to be considered as a single large and composite spray. The lateral spray evolution view (set-up B) shows the origin of the single jets close to the nozzle exit. Four single well-confined arrows-jets appear in the CCD view plane while the last two are covered because they are in the back side. The lateral view of the spray highlights a complex structure of the evolving jets. In fact, bunches or fuel pockets appear in the jet images lighted by higher intensities of the scattered light. This aspect is indicative of a non homogeneous distribution of the fuel inside the jet and is peculiar of the fluidynamic conditions of the injection process.

Numerical model assessment

The numerical simulation of the spray injection within a confined vessel, reproducing the experiment, is realised using as a computational domain a cylinder 0.11 m in diameter and 0.14 m in height. Gasoline injection is assumed to come from a six hole injector mounted on the cylinder top surface with the main axis coinciding with the cylinder axis. Holes are distributed symmetrically on a circumference, with the maximum distance between them of 1.233 mm. The hole diameter is 0.193 mm, hence very small with respect to the cylinder diameter. Reported results refer to a mesh made of 35000 hexaedrical cells, made denser around the spray main axis. Boundary conditions are set as wall for the top and the lateral surfaces, and as a gradient zero condition at the cylinder bottom. Grid invariance of the results is checked. Gravitational effects are considered, as well as turbulent dispersion of particles and break-up. This last is simulated according to the model of Huh-Gosman [4, 5]. Evaporation by the Dukowicz [6] model is also taken into account, although the tested conditions in the vessel are not of an evaporative type.

As previously outlined, input data for the numerical simulation of the spatial-temporal spray dynamics are the measured spray cone angle and the injected mass flow rate as a function of time. Tested strategies are reported in Figure 4. Lack of information regarding the initial droplets size is overcome, as a first step, by resorting to semi-empirical correlations existing in the literature. In particular, eq. (1) is employed [7] which furnishes the initial droplet size as a function of the gasoline surface tension, τ_f, the surrounding gas density, ρ_g and the relative velocity between the fuel and the surrounding air, u_{rel}. C_d is a constant of the order of the unity (indeed taken equal to the unity), and the parameter λ^* derives from the hydrodynamic stability analysis and indicates the dimensionless wavelength of the more unstable perturbations to the liquid-gas interface at the injector exit section.

$$D_{th} = C_d \left(\frac{2\pi\tau_f}{\rho_g u_{rel}^2} \right) \lambda^* \tag{1}$$

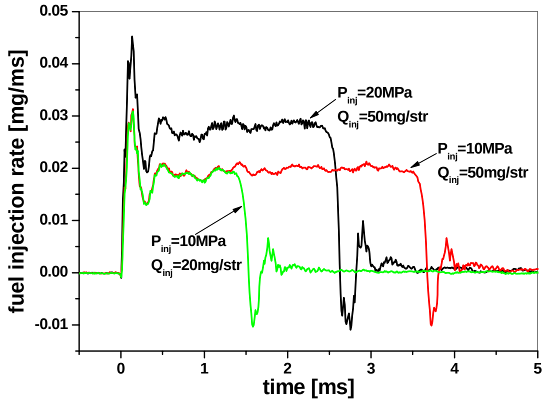

Figure 4. Measured fuel injection rate for 3 strategies

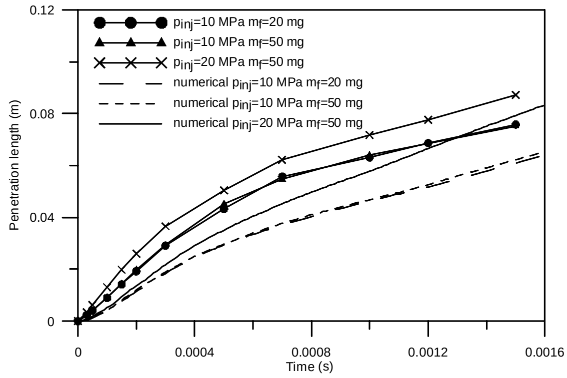

Figure 5. Spray penetration length numerical-experimental comparison before tuning

The relative velocity between the fuel and the surrounding air is evaluated as the ratio between the total injected mass per single hole and per unit of time and the product between the fuel density and the area of the hole itself. Applied to the measured data, this procedure generates a slight difference between the case p_{inj}=10 MPa and m_f=20mg/str and p_{inj}=10 MPa and m_f=50mg/str. Results of the numerical simulations performed for the three injection strategies in terms of penetration length and comparisons with experiments are reported in Figure 5. An underestimation of the penetration length occurs for both the lower and the higher injection pressure. Although the Huh-Gosman model is here used with standard constants, it is found that no appreciable improvements are obtained by changing the C_1 constant up to 60. For this reason a different approach is adopted. A distribution of particle size defined in a probabilistic sense is adopted instead of using a constant value of the initial droplet diameter. Practically, a log-normal distribution is constructed having as expected value the theoretical diameter evaluated on the basis of eq. (1) and a variance equal to 0.5. Figure 6 represents the log-normal distributions built for each of the considered strategies together with the representation of the value of the theoretical diameter. Figure 7 shows the process of constants tuning for both the cases of constant diameter and droplets size distribution for p_{inj}=10 MPa and m_f=20mg/str. In the last case the value of C_1=6 is found to be optimal for the spray description. At the highest pressure an underestimation of the penetration length is found also with C_1=6, which implies the need to increase the value of the variance to 0.6 in the initial droplet size distribution.

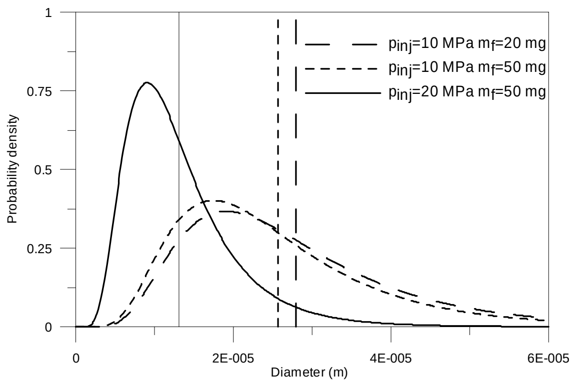

Figure 6. Initial droplets size log-normal distribution

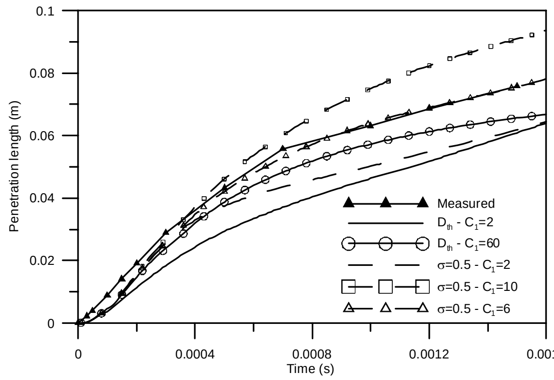

Figure 7. Huh-Gosman model tuning for p_{inj}=10 MPa and m_f= 20 mg/str

The reliability of the proposed model is also demonstrated by the agreement between the value of the arithmetic droplets diameters at a distance of 20 mm from the holes exit section and the experimental data collected by means of the Phase Doppler Anemometry (PDA) technique reported in ref. [1]. Figure 8 shows the experimental and the numerical value of d_{10} as averaged over a volume reproducing the size and position at the experimental one.

Figure 9 reports a visualization of the computed spray at a time of 0.001 s from the SOI, where it is possible to measure the diameter distribution from the hole exit until the tip.

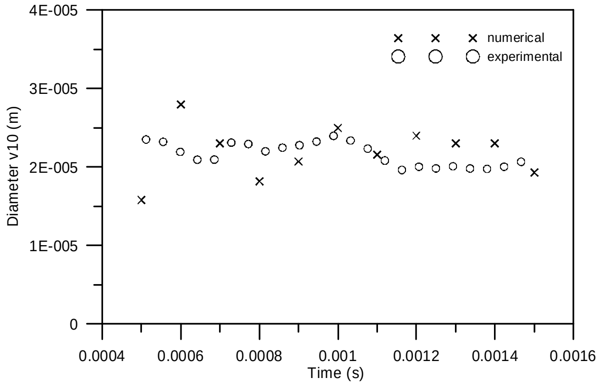

Figure 8. Diameter d_{10} numerical-experimental comparison

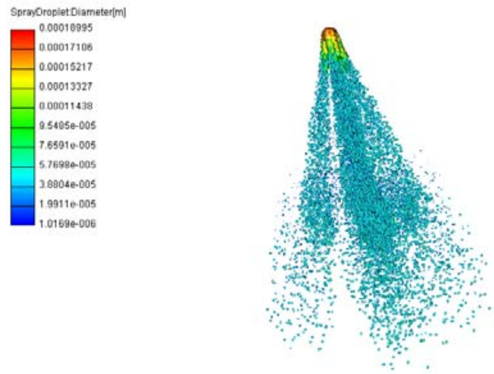

Figure 9. Numerical spray at 0.001 s from SOI

Numerical simulation of the mixture formation process in a GDI SI engine

The assessed numerical model is applied to the simulation of the intake, compression and expansion stroke of a 4-valve GDI engine, exhibiting a pent-roof cylinder head. This allows the study of the mixture formation process, assumed to start at the middle of the intake stroke, namely at the crank angle of maximum valve lift. Fuel injected mass and engine speed are fixed, whereas three different inclinations of the six-hole injector are assumed, namely 45°, 60° and 70°. In all the situations the jet which is more insulated with respect to the others is directed toward the cylinder head. This avoids valve and spark plug wetting even in the most critical situations.

Injection strategy is assumed as coinciding with the previously discussed one at p_{inj}=10 MPa and m_f=50 mg/str. The interaction of the gasoline spray and the piston or cylinder walls is also taken into account. The impingement of the spray on the engine walls gives rise to the deposition of a liquid film on the walls and to a secondary atomisation of the impacting droplets. The process is strongly affected by the value of the wall temperature, the pressure conditions and the velocity and temperature of the surrounding gas. Spray-wall interaction is accounted for within the present work by using the so-called wall-film module of the Fire code. Physical effects characterising the model are interfacial shear forces, gravitational acceleration, pressure gradient in the gas flow, film evaporation, heat transfer between the film and solid wall and gas phase, interaction with impinging droplet spray and air entrainment leading to the film rupture or shearing off at the surface due to high shear forces. The Kuhnke model, in particular, is used in order to account for the hot temperature of the cylinder walls [8].

Some results of the effected computations are reported in Figure 10, where the spray is visualised for two of the three considered injector positions (45° and 70°) just before the crank angle of intake valves closing, which is 603° in the chosen reference system (Top Dead Centre (TDC) is at 720°). Figure 11, instead, represents the distribution of the fuel mass vapour over a plane passing through the spark plug at the crank angle of ignition, which is 676°, for the same inclinations of the injector. The poor quality of charge stratification is evident for the lowest angle of inclination of the spray. Indeed, in the case where the injector is inclined 45° with respect to the cylinder axis, most of the droplets impinge on the piston walls. Finally Figure 12 reports the curves of in-cylinder pressure as a function of the crank angle, thus showing the dramatic influence of the injector position on engine performance.

Conclusions

A numerical model able to simulate the spatio-temporal dynamics of a gasoline spray arising from a multi-hole injector is assessed on the basis of experimental data collected by injecting fuel in a constant volume vessel containing air at controlled pressure and temperature conditions. The measured instantaneous injected mass flow rate and the mean value of the measured cone angle are used as input variables for the model. Initial droplets size at the nozzle exit section is assumed to be constant, according to a semi-empirical correlation, or variable with a probabilistic log-normal distribution of a given variance. This last assumption, after a simple tuning of the employed break-up model, furnishes reasonably predictive results with regards to spray penetration length, overall spray structure and local particle size at a given distance from the hole exit section.

Application of the assessed model to a GDI 4-valve engine, exhibiting a pent-roof cylinder head, is effected by also accounting for the problem of spray-wall interaction. Preliminary computations of the intake, compression and expansion stroke of the considered engine are performed at fixed engine speed and injected gasoline mass, for three different angles of inclination of the injector with respect to the cylinder axis. The paper highlights the use of multi-dimensional engine modelling as a tool for improving the robustness of combustion in a jet-guided GDI engine.

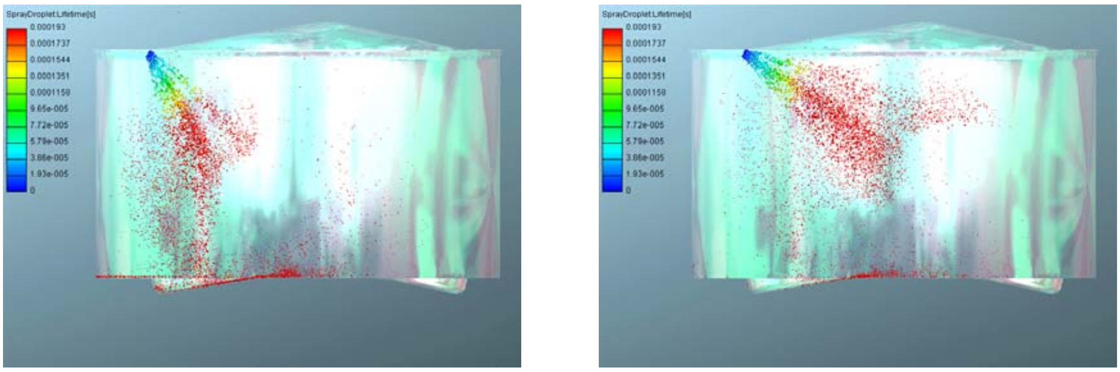

Figure 10. Spray visualisation for injector inclined at 45° (left) and 70° (right) w.r.t. the cylinder axis at 600°

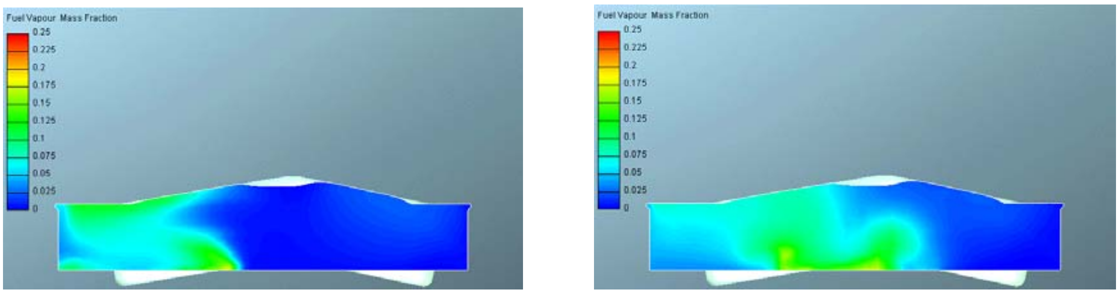

Figure 11. Fuel vapour mass distribution at the ignition time over a plane passing through the spark plug for injector inclined at 45° (left) and 70° (right) w.r.t. the cylinder axis

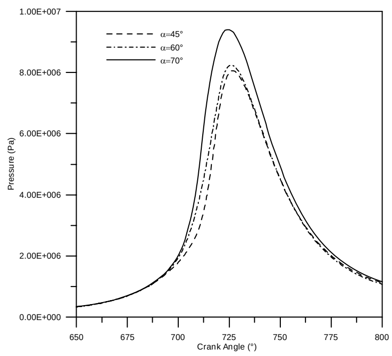

Figure 12. In-cylinder pressure for the three tested engine configurations

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