

Experimental and Numerical Evaluation of Diesel Spray Momentum Flux

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ABSTRACT

In the present work, an experimental and numerical analysis of high pressure Diesel spray evolution is carried out in terms of spray momentum flux time history and instantaneous injection rate. The final goal of spray momentum and of injection rate analyses is the evaluation of the nozzle outlet flow characteristics and of the nozzle internal geometry possible influences on cavitation phenomena, which are of primary importance for the spray evolution. Further, the evaluation of the flow characteristics at the nozzle exit is fundamental in order to obtain reliable boundary conditions for injection process 3D simulation.

In this paper, spray momentum data obtained in ambient temperature, high counter-pressure conditions at the Perugia University Spray Laboratory are presented and compared with the results of 3D simulations of the momentum rig itself. The experimental tests, performed using a commercial common-rail injector, include high speed imaging of the spray during momentum tests and the measurement of instantaneous injection rate for a more detailed comparison with the numerical analysis. Numerical 3D simulations allowed to evaluate the actual contribution to global spray momentum given by the liquid phase and by the gaseous phase, as a function of time and target distance from nozzle. This analysis allowed to explain the observed influences of the measurement procedure on the spray momentum flux experimental data.

In particular, the present CFD analysis highlighted a significant contribution to the jet momentum flux provided by gaseous phase, which tends to become predominant with growing distances from the nozzle.

The findings suggested that the target design and position can affect significantly the spray momentum flux measurement. In some operating conditions, unexpected trends of the spray momentum time integral as a function of the target distance were obtained, suggesting that main hypotheses on which spray momentum measurement devices are based – i.e. orthogonal flow deviation – may not hold true for some system configurations.

INTRODUCTION

In a Diesel engine, in order to achieve an efficient combustion process with moderate "engine out" emissions, the optimization of the injection process in terms of both fuel injection rate and spray characteristics is crucial. In fact, the spray evolution in terms of atomization, spray penetration, spray cone angle and air entrainment has a fundamental impact on the local air-fuel mixture formation process and hence on combustion and on pollutant formation processes [1-5].

As reported in literature, the spray evolution largely depends on its momentum flux [5], mainly in terms of air entrainment and mixing potential. Hence, the knowledge of the spray momentum time-history and spatial distribution could lead a significant contribution in the overall mixing process optimization. The spray global momentum flux measurement can also support in the analysis of other key points of the injection process such as cavitation inside the nozzle hole channel, which significantly affects the flow discharge and atomization processes. In detail, the knowledge of the fuel mass injection rate and of the fuel momentum flux during the injection process allows, under some assumptions, the estimation of the flow velocity and of the equivalent flow section at the exit of the injector hole [6-9]. The spray

momentum flux is measured by an indirect method in terms of impact force of the spray onto a flat surface (named target) perpendicular to the spray main axis: in steady flow conditions, assuming that the spray is deviated by the target having null residual velocity components in axial direction, the measured axial force on the target is equivalent to the change in the flow momentum, i. e. is equal to the spray momentum flux along its main axis. If the target is large enough to interact with the entire spray, the global momentum is measured, otherwise by using a smaller target positioned in different locations, it is possible to build spray momentum distribution maps. As reported in literature [3, 8], by analysing the local spray momentum flux time-history, it is also possible to deduce interesting information about the spray local atomization level.

Given the relevance of the spray momentum flux, it is important to analyse the measurement procedure details (mainly the target size and position, along with the appropriate time-window to be considered for the analysis) and the effects that these can have on the results.

This work is part of a research activity that the same group carried out in last years dealing with injection systems an spray analysis [11-14]. In the present paper, the spray overall momentum measurement is investigated. The spray-target impact process in high counter-pressure conditions was experimentally and numerically investigated by studying the spray impact force time-history and spray momentum having the injection pressure, the counter pressure, the target distance and size as main analysis parameters. In order to better understand the spray momentum evolution process, the time-history contribution of the liquid and the gaseous phases to the measured force was numerically analysed. As will be detailed in the following Sections, following the spray evolution, a progressively predominant contribution of the gaseous phase to the overall spray momentum was obtained.

The present work is divided in the following Sections: after a brief Background Section, a description of the experimental set-up and procedures is reported, while in the next Section the numerical set-up for the CFD-3D simulations is described; finally, the main experimental results are reported along with some data analysis based also on combined experimental and numerical results.

BACKGROUND

The flow discharge from a high-pressure injector nozzle hole is a complex phenomenon in which the injection fluid experiences a strong acceleration from the steady, very high pressure conditions inside the injector sac to high velocity, relatively low pressure conditions inside the combustion chamber. The sudden flow acceleration and the peculiar flow patterns inside the nozzle hole can cause the static pressure downstream the hole entrance to fall below the fluid vapour pressure: in this conditions,

the onset of fluid cavitation is observed, with the formation of fluid vapour bubbles flowing the discharge channel along with the liquid phase, significantly influencing the spray evolution. The intensity of cavitation phenomena in the injection process depends mainly on the cavitation number (i.e. on the pressure drop across the nozzle hole and on the fluid vapour pressure) and on the nozzle hole design (inlet rounding radii, conicity, L/D ratio).

In these complex flow conditions, the definition of the effective discharge characteristics (mainly velocity and flow section) at the nozzle hole exit is a hard task. As already reported in literature (e.g. Payri et al. [6-9]), a simplified approach can be used to face the problem.

The liquid-vapour mixture exiting the nozzle hole will be characterized by a mass flow rate $\dot{m}_f$ and by a momentum flux $\dot{M}_f$ defined as follows:

$$\text{Eq. 1} \quad \dot{m}_f = \int_{S_o} \rho v dS$$

$$\text{Eq. 2} \quad \dot{M}_f = \int_{S_o} \rho v^2 dS$$

Assuming that:

- the liquid portion of the flow exits the hole with a uniform velocity v_{eff} ;
- the liquid portion of the flow occupies the S_{eff} portion of the S_o geometrical hole outlet section;
- the vapour contribution to both mass flow and momentum flow is negligible;

the expressions for mass flow rate and for momentum flux can be simplified to:

$$\text{Eq. 3} \quad \dot{m}_f = \rho_l v_{eff} S_{eff}; \quad \dot{M}_f = \rho_l v_{eff}^2 S_{eff}$$

Consequently, the effective flow discharge velocity v_{eff} and the effective flow section S_{eff} can be evaluated by:

$$\text{Eq. 4} \quad v_{eff} = \frac{\dot{M}_f}{\dot{m}_f}; \quad S_{eff} = \frac{\dot{m}_f^2}{\rho_l \dot{M}_f}$$

From Eq. 3 and Eq. 4, the definition of the velocity reduction C_v and flow section reduction C_s coefficients follows:

$$\text{Eq. 5} \quad C_v = \frac{v_{eff}}{\sqrt{\frac{2 \Delta P}{\rho}}} = \frac{v_{eff}}{v_{th}}; \quad C_s = \frac{S_{eff}}{S_o}$$

As can be seen, the evaluation of two important flow quantities as v_{eff} and S_{eff} requires both the mass flow rate and the spray momentum flux measurement.

While the mass flow rate measurement is possible by different, well established techniques and commercial devices [15, 16], the spray momentum flux experimental evaluation is not so widespread. Hence some criticism of the possible momentum flux measurement technique could be convenient.

The spray momentum flux can be measured in an indirect way by the experimental setup sketched in Figure 1. Basically, the instrument measures the force generated by the impact of the spray on a flat surface (target) orthogonal to the spray axis. The spray-target interaction is governed by the momentum conservation equation, that for the more general case considering the fluid enclosed in a control volume V_c by its boundary surface S_c can be written as follows:

$$\text{Eq. 6} \quad \vec{F} = \frac{\partial}{\partial t} \iiint_{V_c} \rho \vec{v} dV + \iint_{S_c} \rho \vec{v} (\vec{v} \cdot \vec{n}) dS$$

where $\vec{v}$ is the flow velocity vector and $\vec{F}$ is the resultant of the forces acting both on the control volume boundary surfaces (e.g. normal and shear stresses) and on the volume fluid mass (e.g. the weight force).

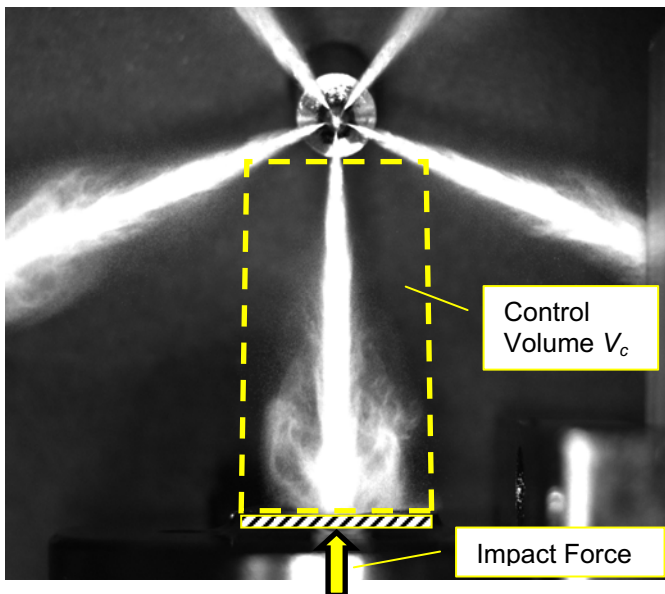


Figure 1 – Sketch of a spray momentum flux measurement device.

In the present analysis, the fluid body to be considered is the spray (liquid and gaseous phases) and the surrounding air located between the nozzle orifice and the target. The control volume can be assumed to be a cylinder whose height is equal to the nozzle-target distance, whose diameter is equal to the target diameter and with the basis lying on the target itself (see Figure 1). Applying Eq. 6 to such a control volume and projecting it along the spray axis (Z axis), results in the following:

$$\text{Eq. 7} \quad F_z = \underbrace{\frac{\partial}{\partial t} \iiint_{V_c} \rho v_z dV}_{\text{Unsteady term}} + \underbrace{\iint_{S_c} \rho v_z (\vec{v} \cdot \vec{n}) dS}_{\text{Convective term (or flux term)}}$$

Ext. force

In Eq. 7, the term F_z can be assumed to be the surface action of the target onto the fluid body, being the weight force on V_c and the stresses on the remaining part of S_c negligible (it is worth noting that also the liquid pressure force at the nozzle exit practically vanishes, since the pressure value equates the ambient value); thus F_z is in modulus equal to the force measured by the sensor under the target. Further, if a correct operation for the target is assumed (i.e. the fluid leaving the control volume has null v_z velocity component and air entrainment through S_c is negligible) the only flux term to be considered is the momentum contribution from the nozzle exit area. The unsteady term accounts for the difference between the momentum flux from the nozzle and the measured force during transient spray operation and can be neglected only if steady spray-target interaction is achieved, which depends on both the injection parameters (injection pressure, counter-pressure, ET) and on the momentum rig design (nozzle-target distance, target diameter). Only in steady flow conditions the measured spray force can be assumed to be equal (in modulus) to the spray momentum flux.

Finally, as will be shown in the following sections, particular care is needed to correctly estimate the overall spray momentum supplied during the injection process: in time integrating Eq. 7, attention should be paid in choosing a final integration time in which the time integral of the unsteady term can be reasonably considered negligible, i.e. with steady (or null) v_z velocity components.

In the following sections, the spray-target interaction is analysed in order to investigate the dependences of the measure results from the device setup and, by a joint experimentally and numerically approach, to examine the possible sources of inaccuracy.

EXPERIMENTAL SET UP AND TEST PLAN

In order to analyse the spray-target interaction for current DI Diesel sprays operation, a commercial common rail injector was used (Bosch CRIP1-MI) for the tests and for the 3D simulations. The system was characterized in terms of injection mass rate, spray momentum flux and overall spray structure by an imaging analysis. In the following, the injection apparatus along with the used experimental rigs are briefly described. Finally, the experimental test plan is reported.

INJECTION SYSTEM – The present spray analysis was performed with a production Bosch CRIP1-MI injector equipped with a mini-sac, symmetric five-hole nozzle, with 0.13 mm hole diameter and a 1.3 Kg connectivity factor.

For the present tests, the injector is fed from a standard common rail connected to a static pressure generation system (AEA), which is able to supply fluid at pressure levels ranging from 50 bar to 2000 bar with pressure ripple being within $\pm 0.1\%$ f.s. in stand-by mode. In all the tests described in the present work, the injection apparatus was operated with a standard ISO 4113 calibration fluid (Table 1).

Table 1 – ISO 4113 calibration fluid properties.

Density at 15 °C, [kg/m ³]	823.9
Dynamic viscosity at 40 °C, [kg/m·s]	0.00208
Surface tension coeff. at 20 °C [N/m]	0.043

The injector is driven by an EFS IPOD8232 programmable ECU, which is triggered by the PC-based test rig control and data acquisition system.

INJECTION RATE RIG – The injection rate was measured by a self-developed device (STS-Shot-to-Shot) based on the Zeuch Method [16]: the injection is performed in a closed, constant volume vessel filled with pressurized injection fluid. The pressure level in the vessel before the injection (“base level”) can be varied from 10 bar to 80 bar. The injection of the ΔV fuel volume raises the chamber pressure with a ΔP proportional to the fluid average bulk modulus k . Hence, it is possible to calculate the instantaneous injection rate according to the following Eq. 8:

$$\text{Eq. 8} \quad \Delta P = \frac{k}{V} \Delta V \Rightarrow \dot{Q}(t) = \frac{dV}{dt} = \frac{V}{k} \frac{dP}{dt}$$

The STS device allows the injected volume and injection rate profile dispersion analyses. The typical STS accuracy for mean injected volume is better than $\pm 99.7\%$ for injected volumes higher than 0.5 mm^3 . More details about this measuring device are reported in previous works [17, 18].

SPRAY IMAGING and TEST VESSEL – The spray imaging systems (described in detail in [12, 14, 17, 19]) is based on a CCD camera (PCO Sensicam) synchronised with the injection event and a Nd-Yag laser (532 nm, 10 ns pulse duration) used as lighting system via an optical-fiber device. The images acquisition is performed by recording sets of images, each set being pertaining to a fixed delay from the trigger (e.g. the start of Energizing Time); hence, each set can be considered representative of the spray evolution at the fixed delay (ensemble average), given an adequate number of images per set to compensate the event-to-event dispersion (normally, 20 images/set). The off-line image digital analysis allows the definition of the main spray characteristics: penetration, cone angle, global shape.

The test vessel used for the spray imaging (Figure 2) and for the momentum flux measurement is designed for an 8.5 MPa internal pressure with 450 °C temperature. The injector is tilt-mounted (15°) in order to have one of the jets vertical along the test chamber Z-axis. Imaging during momentum measurement is possible in order to better understand the spray-target interaction.

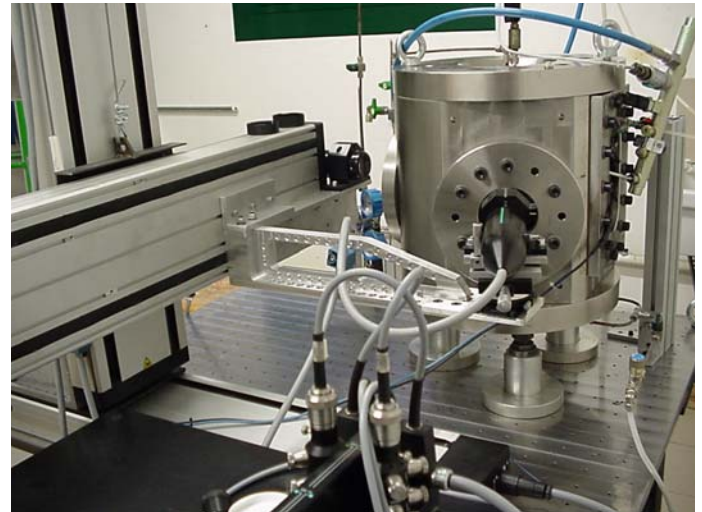


Figure 2 – The imaging and momentum test vessel. A XYZ traverse system for PDA analysis is also visible.

MOMENTUM FLUX RIG – The spray momentum flux measurement is based on a piezoelectric force sensor (Kistler type 9215 coupled with a Kistler type 5011 charge amplifier) which collects the impact force of the spray onto a small surface orthogonal to the spray main axis (target). The target-force sensor assembly is mounted on a three-axes Cartesian positioning system inside the pressurized test vessel (Figure 3). The positioning system is equipped with three stepper motors which allows the target-sensor assembly to be moved for a $\pm 13 \text{ mm}$ travel for the X and Y axes from the central position and for a 50 mm travel along the Z axis (the minimum target distance along Z axis from the nozzle exit is 10 mm).

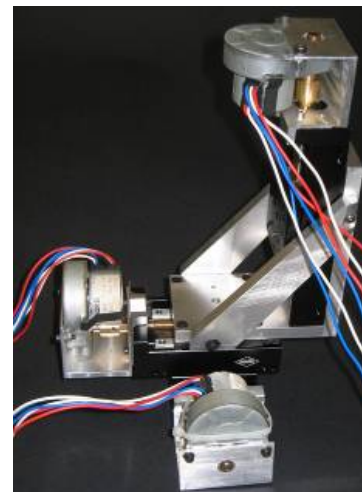


Figure 3 – Target and force sensor positioning system.