

Analysis of Diesel Spray Momentum Flux Spatial Distribution

2011-01-0682

Published
04/12/2011

Lucio Postrioti and Michele Battistoni
Universita degli Studi di Perugia

Carmine Ungaro and Alessandro Mariani
Gruppo Luccioni

Copyright © 2011 SAE International

doi:[10.4271/2011-01-0682](https://doi.org/10.4271/2011-01-0682)

ABSTRACT

In the present paper the results of an experimental and numerical analysis of a common-rail, high pressure Diesel spray evolving in high counter pressure conditions is reported. The experimental study was carried out mainly in terms of spray momentum flux indirect measurement by the spray impact method; the measurement of the impact force time-histories, along with the CFD analysis of the same phenomenon, gave interesting insight in the internal spray structure. As well known, the overall spray structure momentum flux along with the injection rate measurements can be used to derive significant details about the in-nozzle flow and cavitation phenomena intensity. The same global spray momentum and momentum flux measurement can be useful in determining the jet-to-jet un-uniformities also in transient, engine-typical injection conditions which can assist in the matching process between the injection system and the combustion chamber design.

In the present paper, the potential in the internal spray structure analysis by means of local spray momentum flux distribution investigation is evaluated. To obtain such momentum flux distribution maps, a variant in the global spray momentum measurement technique is evaluated. The use of an adaptor to the momentum flux measurement rig is discussed, numerically analyzed and tested on a dedicated experimental bench. Some results pertaining to solenoid-actuated common rail injectors are presented and discussed in terms of spray distribution irregularities, momentum profiles and differences in the spray structure obtained for the different jets emerging from the nozzle.

INTRODUCTION

Despite the progressive hybridization of automotive powertrain systems and its promising contribution of the global CO₂ emission reduction, a great effort is being made by engine Manufacturers to increase conventional, combustion-based power system efficiency. For internal combustion engines, that will continue to act a major role in the mobility scenario for many years, the potential in efficiency improvement depends to a large extent on the combustion control managing capabilities. To this end, direct injected engines, both spark ignited and Diesel, require a more and more sophisticated control on the fuel injection process characteristics, which have to be defined to match both the combustion chamber design and the desired combustion process development in a large range of operating conditions [1, 2, 3, 4, 5]. Managing the injection process means the ability to control many and often contrasting phenomena, according to severe constraints in terms of fuel metering accuracy, injection rate shaping, evolving spray form, fuel atomization and mixing with surrounding air. Besides these classical issues, in recent years the non-uniformity among the different sprays in terms of flow rate, jet structure and evolution is assuming a progressively higher importance.

In the present paper, following the previous studies on spray global momentum by the same research group [12, 13], the development of a measurement technique for the local spray momentum flux distribution inside the jet structure is presented and discussed. While the global momentum analysis can assist in both the evaluation of cavitation intensity and in jet-to-jet un-uniformities in terms of injected

flow momentum, the spray momentum distribution study is a further step in the spray evolution comprehension. These two experimental techniques can significantly contribute in both the injection process quality direct analysis and in the injection processes CFD study, by supplying final checks and boundary conditions data. In this sense, the global and local momentum measurement can be considered an experimental approach complementary to more traditional ones, such as global injection rate measurement, imaging and Laser Doppler Velocimetry (LDV). Injection rate measurement can quantify the fuel delivery rate and its time-integral from the entire injector, without any knowledge of the discrepancies on the flow rates from the single holes. Visualization can be a powerful and intuitive approach to investigate the overall sprays structure and differences among jets, but its effectiveness is limited by the lack of quantitative data about the origin of different jet characteristics, which largely depends on the spray momentum flux [6]. Doppler-effect-based optical techniques (such as Phase Doppler Anemometry) or Particle Image Velocimetry are very powerful in principle but are limited in terms of feasibility for the analysis of very dense sprays or too complex for mass production testing.

As in the previous papers by the same research group, the approach to the study of global and local momentum measurement is based on both CFD and experimental activity. The development of the local momentum flux measurement rig is based on the CFD analysis of the spray-sensing device interaction, in order to define different possible device configurations. Among these, the most promising ones were tested, resulting in the development of a dedicated test bench, which allows a fast and complete analysis of local and global spray momentum characteristics for all the jets emerging from a nozzle, in a pressurized test vessel.

BACKGROUND

The overall spray momentum flux measurement in steady state conditions is a well assessed technique [7, 8, 9, 10, 11], used to evaluate the influence of the nozzle internal design on the fuel flow mainly in terms of cavitation intensity. To evaluate the global spray momentum flux, the impact force of the spray onto an orthogonal plate (target) is measured (*Figure 1*); the plate is kept at a fixed distance from the nozzle exit and its diameter is much larger than the spray to avoid the loss of peripheral portions of the jet itself. As an effect of the impact, the spray is sideward deviated in such a way to lose any axial velocity component. The application of the momentum conservation equation (Eq. (1)) to the control volume sketched in *Figure 1* ensures that, when the steady state conditions are achieved, the measured impact force must equate the global spray momentum flux.

$$\vec{F} = \frac{\partial}{\partial t} \iiint_V \rho \vec{v} dV + \iint_S \rho \vec{v} (\vec{v} \cdot \vec{n}) dS \quad (1)$$

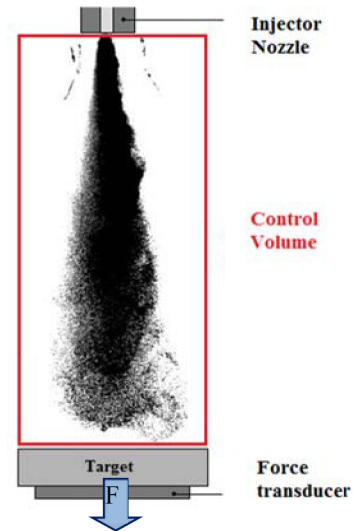


Figure 1. Sketch of a spray momentum measurement rig and flow control volume.

This approach in the evaluation of the global momentum flux in steady state conditions can be used to derive interesting awareness about the liquid-vapor mixture flow emerging from the nozzle. If additional hypotheses are assumed - uniform flow velocity v_{eff} at the nozzle exit section A_{eff} , separation between the regions occupied by the two-phases and negligible contribution of the vapor phase to the spray momentum, the instantaneous mass flow rate $\dot{m}$ and momentum flux $\dot{M}$ can be expressed as :

$$\dot{m} = \rho_l v_{eff} S_{eff} \quad \dot{M} = \rho_l v_{eff}^2 S_{eff} \quad (2)$$

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

$$v_{eff} = \frac{\dot{M}}{\dot{m}}; \quad S_{eff} = \frac{\dot{m}^2}{\rho_l \dot{M}} \quad (3)$$

From the Eq. (2) and (3), defining the global discharge coefficient as $C_d = C_v \cdot C_s$, the following definitions for the velocity reduction C_v and flow section reduction C_s coefficients follow:

$$C_v = \frac{v_{eff}}{\sqrt{2\Delta P/\rho}} = \frac{v_{eff}}{v_{th}}; \quad C_s = \frac{S_{eff}}{S_o} \quad (4)$$

The correct application of the previously described analysis requires that steady state flow conditions are achieved, and to this end (for the case of common-rail injection system) Energizing Time settings typically ranging from 3 ms to 5 ms are applied, which are quite far from engine-like operating conditions. Further, for the momentum flux evaluation, only the mean value of the spray impact force during the middle part of the injection process (i.e. skipping both the injection on-set and closing transients) is considered. This testing procedure is to be considered fully appropriate if the subject of the analysis is actually the nozzle behaviour in terms of discharge capabilities and cavitation intensity in steady needle lift conditions. On the other hand, the steady flow momentum analysis cannot give any significant information about the injection system behaviour during injection events that don't achieve steady conditions, which is the most diffused operation mode for automotive Diesel injection systems. For a transient injection analysis the complete momentum conservation equation (Eq. (1)) must be applied to the fluid control volume: the inertia of the fluid inside the control volume and the possibly non-null velocity components of the fluid abandoning the control volume itself could be significant terms that affect the coincidence between what is measured in terms of impact force time-history and the momentum flux time-history at the nozzle exit.

In previous papers, the Authors discussed the application of the impact force measurement as an indirect method to estimate the spray global momentum flux also in transient conditions [12, 13]. A numerical study about the contributions of the different terms in the momentum conservation equation when applied to Diesel injection was carried out, supported by dedicated experiments of the spray-target interaction mechanism. This analysis suggested that, using a properly designed experimental system, it is possible to minimize the discrepancies between the measured impact force time-history and the momentum flux time-profile in transient conditions. As a consequence, the investigation about the global spray momentum flux in engine-like injection events is feasible, allowing the quantitative analysis of the injection system in terms of single jet behavior. As an application example, jet-to-jet development discrepancies that are sometimes evident in the beginning of many injection events and that are even more significant in very short injection events (i.e. in idle or in very low load conditions) often result in significant differences between jets from the same nozzle in terms of final penetration, diffusion and, hence, mixing potential. These diversities are likely to be due to peculiar needle-nozzle interactions in the opening phase rather than to defects in the nozzle holes manufacturing, as it

is often suggested by the fact that jets which are less penetrating in the first part of the injection event, later increase significantly their development rate with respect to the others. The spray structure visualization allows a quantitative analysis of the injection results in terms of jet dimensional growth, but doesn't give any support in terms of understanding the origin of different evolutions. On the other hand, the transient analysis of the single jet global momentum allows the quantitative evaluation of the driving force of different spray evolutions, which clearly cannot be captured at all by a simple steady state momentum analysis.

In order to further increase the spray investigation capabilities, a proper insight of the momentum flux distribution inside the spray structure would be of great importance, which implies the ability to correctly detect the spray momentum for small flow-tubes inside the spray flow structure, what in the following will be named as "Local Momentum Flux". Clearly the spatial integration of the local momentum flux should equate the "Global Momentum Flux" intended as the momentum flux of the entire spray flow structure. Kampmann et al. [5] showed the possible information obtainable by a very small diameter momentum probe (target diameter $\phi=2\text{mm}$) positioned at various distances from the nozzle exit and in different angular position with respect to the spray nominal axis. In [5], the research targets were mainly the comparison of the spray atomization levels and the spray cone angle detection with different nozzle configuration, both of which were assumed to be efficiently indicated by the local value of the spray impact force on the target.

In the present research activity, a newly developed device will be presented which allows the local spray momentum distribution measurement for each single jet emerging from the nozzle of a Diesel injection system. This analysis can be carried out in high counter pressure conditions at different distances from the nozzle exit, offering the potential of describing the local spray momentum flux distribution along surfaces (according to a Cartesian or spherical coordinate system) both in terms of instantaneous values (momentum flux) and time integrated values (momentum). This kind of information can be of great importance both in the direct evaluation of the spray evolution quality in different operating conditions and in building a knowledge base about the spray structure and time evolution to be used as reference for CFD spray simulations. The development of the local momentum detection system was carried out by an integrated experimental and numerical approach, in which the role played by CFD was mainly the suggestion and a first analysis of possible configurations for the detection device, which were later experimentally assessed by the test rig.

CFD MODEL

Spray CFD simulations were carried out to analyze the details of a free jet and of the corresponding impacting jet in specific injection conditions or test rig designs. All the simulations refer to injections in a constant volume vessel at given backpressure and ambient temperature.

A preliminary validation of the CFD spray model was already described in [12], where free spray tip penetrations, transient global momentum flux values and impact force time-integrals were compared to experimental data. Good agreements were achieved on all these macroscopic spray quantities.

In this work, the main objective of spray CFD simulations was the analysis of local distribution of momentum flux in space and time and its comparison with experimental local analysis. The details of the numerical model used in this work are briefly summarized in the following.

Spray simulations have been carried out by means of the CFD-3D code AVL Fire [27]. The Semi-Implicit Method for Pressure Linked Equations solving algorithm was used. Temporal discretization was performed using a first-order (Euler) implicit differencing scheme, with a time-step of 5E-06 s. Standard $k-\epsilon$ model turbulence model was employed. Parcels of liquid drops are released at each time-step from the location of the hole exit area and their equations of motion are solved according to a typical Lagrangian approach. Drops collisions and coalescence phenomena were modeled according to Schmidt-O'Rourke approach. Spray-wall interaction was modeled using the Walljet2 model proposed by Naber and Reitz [28]. The Wave model [29], as proposed by Reitz et al., was used as secondary break-up model. Main tuning constants were set to $C_1=0.61$ and $C_2=30$.

As already mentioned, the same injection conditions were used both for free spray configuration (i.e. without target) and for impacting jet configuration (with target).

Blob injection method was used for primary atomization. Location of parcel release was randomly chosen within the area of the nozzle exit hole, releasing 80 parcels per time-step. Constant particle size was used. The value was set equal to the effective hole exit diameter: this was computed using a section reduction coefficient C_s applied to the hole area (determined according to the usual steady state characterization of injectors by means of impact force and injection rate measurements, see [12, 13]).

Two methods were used to assign droplet initial velocities.

1. In the first and simplified approach, the time dependent actual injection velocity was determined from the specified injection rate, as measured in the experimental test rig, and from the nozzle hole effective area, i.e. $v_{inj}(t)=Q(t)/(S_o C_s)$. In

the present work, $C_s = 0.934$. In this approach, for a given time, all droplets have the same starting velocity, disregarding of their release location: as an example no radial velocity gradients exist.

2. In the second approach a preliminary simulation of the transient 3D flow field of the hole internal flow, using an Eulerian-Eulerian two-fluid method, has been carried out. In this way a nozzle interface is set-up between the internal hole domain and the external Lagrangian spray calculation [27, 30]. The concept of the nozzle interface is to use the data of the two phase flow calculation inside the nozzle as a start condition for the Euler / Lagrange spray calculation. There is no direct coupling between the internal nozzle flow simulation and the spray calculation. This means that the nozzle data only serves as a boundary condition for the Lagrangian spray. In the interface the values of the liquid velocities, densities and the turbulence quantities are written into a data file. During the Lagrangian spray simulation the start values will be linearly interpolated, in time and space, from the available data sets. This method is supposed to offer two main advantages: it delivers more reliable start conditions for the injection velocity; it offers the possibility to apply more detailed primary break-up models, as there is detailed information about the turbulence quantities and the cavitation bubbles available at the nozzle exit. As a final remark, with this approach, at each time, all droplets have different starting velocity which depends on their release physical location.

A special post-processing algorithm has also been developed, for the evaluation of the liquid contribution to the force exerted on the target (impacting jet cases), or to the global momentum flux through a virtual plane (free jet cases). While the gaseous phase contribution to the global momentum flux can be easily evaluated from CFD results both for free or impacting jets (in terms of gaseous phase momentum or in terms of static pressure exerted on the target, respectively), the evaluation of the liquid phase contribution to the global spray momentum requires an *ad hoc* external routine. Concisely, at each time, all drops which are going to impact on (or to cross) the surface, within an arbitrary small time τ , are taken into account for the liquid force (or liquid momentum flux) evaluation; the impact force (or momentum flux) due to the liquid phase can hence be estimated as the ratio of the selected drops momentum to the time interval τ . Extensive details of the algorithm have been presented in [12].

LOCAL SPRAY MOMENTUM FLUX RIG DEVELOPMENT

In order to develop a measuring device able to detect the spray momentum flux distribution along a generic surface, the basic concept applied was to measure the momentum flux of a small portion of the spray (a small flow tube) minimizing

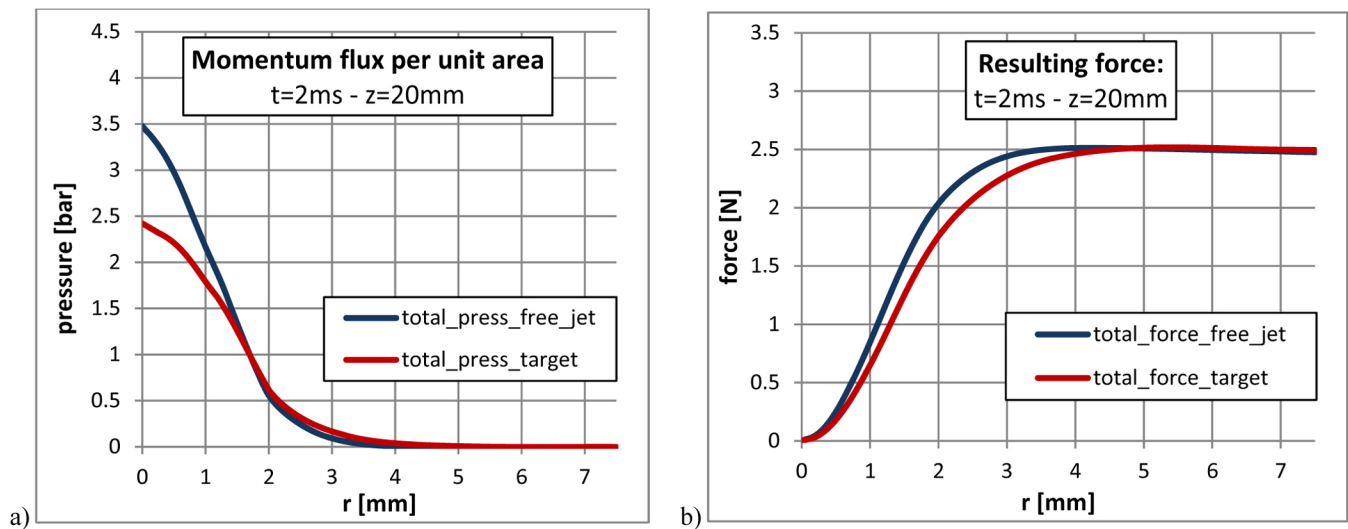


Figure 2. Pressure distribution in impacting and free jet configurations on the target plane, a). Resulting Total Forces, b).

the interactions between the analyzed part of the jet and the surroundings, with the intention of obtaining local momentum flux data equivalent to the momentum flux of the examined portion in the free spray generated by the same injection conditions. Unfortunately, the momentum flux measurement requires an indirect detection, as above reported, by means of an impact onto a surface orthogonal to the spray axis, so to lose its axial velocity component. To evaluate the effect of the target insertion on the spray momentum flux distribution, some CFD computations were set-up, comparing the total pressure distribution exerted by the spray on the target (gaseous and liquid phases) in a global momentum measurement configuration and the corresponding total pressure distribution on a virtual surface in case of free spray evolution, which clearly is the true analysis objective. In order to easily compare the free-jet and the impacting configurations in terms of momentum flux, for the free-jet cases the two-phase flow momentum flux content was computed in area-specific terms, being so described as a pressure, in a way similar to the impacting configuration; this approach was also followed in the rest of the present work. Given the general intent of this step in the research project, in order to simplify the analysis, a virtual, simplified injection process was simulated, using the approach #2 previously described: the needle lift was assumed to be composed by a starting linear ramp up to 0.5 ms, a constant middle part up to 2.5 ms and a linearly decreasing ramp up to 3 ms; injection parameters were fixed at Prail 1200 bar, ET 3000 μs , Pvessel 50 bar. The numerical code sub-models settings were assumed as described in the previous paragraph. In [Figure 2](#) the pressure radial profiles for the examined configurations are reported at $Z=20\text{mm}$ from the nozzle exit and at 2 ms from the injection start. In the same [Figure 2](#), the resulting cumulative force acting on the target or on the virtual surface for the two examined configurations is also reported.

As can be seen, the total pressure distributions are completely different: as expected, the target insertion depletes the distribution peak and enlarges the pressure profile as a result of the flow structure deviation from the spray axial to the orthogonal direction. On the other hand, it's very interesting to note ([Figure 2b](#)) that the total force acting on the target and on the virtual surface for the free jet configuration is the same: this is a significant substantiation of the target validity as global momentum measuring tool. Given the significant influence exerted by the target on the flow structure, any local momentum measuring device based on the detection of the local pressure along a large flat surface orthogonal to the spray axis would be intrinsically invasive: such a support for the sensitive element would lead to the measure of a pressure distribution relevant to a flow structure which is completely different from the free jet configuration. In order to design a proper local momentum detector, the pressure distribution for the impacting configuration was analyzed ([Figure 3](#)): as can be seen, the over-pressure zone (having the mean domain pressure as reference) caused by the spray impact is limited to a very small volume on top of the target. In the simulated configuration, just 2 mm upstream from the target surface the over pressure to the mean vessel pressure value is negligible.

This results seems to suggest that, even if the target affects the static pressure distribution in the spray-target impact zone, on a $Z=\text{const}$ surface few millimeters upstream the target, the momentum flux distribution in the impacting configuration should be not so different from the corresponding distribution in the free jet configuration. In the following [Figure 4](#), a comparison of the computed momentum flux distribution for the target configuration and for the free-jet configuration, at $Z=18\text{ mm}$ (2 mm upstream the target) is reported.

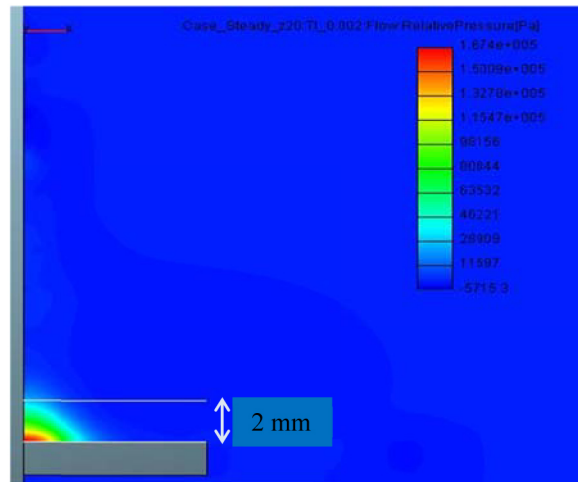


Figure 3. Pressure distribution in impacting spray configuration.

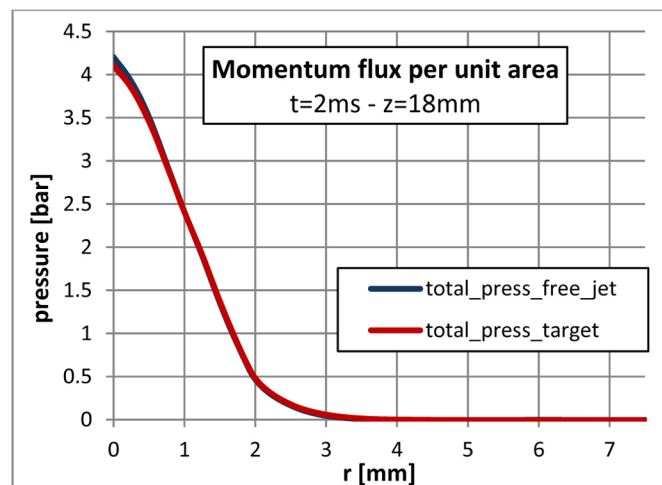


Figure 4. Pressure distribution in impacting and free jet configurations 2 mm upstream the target plane.

The very good agreement between the CFD momentum flux distribution results for the free jet and the target configurations suggests that the local momentum flux distribution detection should be possible, provided that peculiar attention is applied to the detector design. This should sense the local jet momentum in a position in which the flow pattern is not affected by the sensing system itself, so to obtain a momentum flux map equivalent to one relevant to the free jet configuration. Unfortunately, as previously mentioned, the momentum measurement can be obtained only in an in-direct way by inserting a deflecting obstacle to the flow and measuring the resulting impact force.

To try to overcome these difficulties, the momentum measurement rig was modified with respect to the global momentum configuration (Figure 1) by the adoption of suitable adapters for the local momentum flux measure. In any configuration, the adapter acts like a spatial filter to

restrict the momentum measurement to a small portion of the spray structure. Different adapters were considered and tested, among these the most interesting configurations are (Figure 5):

- Cone Adapter
- Cone+Pin Adapter

In the Cone Adapter configuration (Figure 5a), a hollow conical element with a small hole on its top is used to extract a small flow-tube from the spray structure. This small spray fraction is free to evolve downward the cone and impacts on a target mounted on the force sensor. The target is large enough to easily accommodate the small jet emerging from the cone hole, ensuring a complete orthogonal deviation and hence a correct momentum flux estimation for the examined spray portion. By this approach, the local momentum flux measurement is carried out with the same approach of the global momentum flux detection (the target and the force