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Andrea Cavicchi, Simone Sparacino, Fabio Berni, Lucio Postrioti, and Stefano Fontanesi

Evaluation of the Single Jet Flow Rate for a Multi-Hole GDI Nozzle

Andrea Cavicchi[1 a)], Simone Sparacino[2], Fabio Berni[2], Lucio Postrioti[1 b)], Stefano Fontanesi[2 c)]

[1]*Dipartimento di Ingegneria – Università degli Studi di Perugia, Perugia, Italy*
[2] *Dipartimento di Ingegneria – DIEF – Università di Modena e Reggio Emilia, Modena, Italy*

[a)]Corresponding author: andrea.cavicchi@unipg.it
[b)] lucio.postrioti@unipg.it
[c)] stefano.fontanesi@unimore.it

Abstract. Fuel injectors featuring differentiated hole-to-hole dimensions improve the fuel distribution in the cylinder ensuring a more efficient and cleaner combustion for GDI (Gasoline Direct Injection) engines. A proper diagnostic system able to detect the actual fuel flow rate exiting each hole of a GDI nozzle is requested in order to optimize the matching between the spray and the combustion chamber.
Measuring the spray impact force of a single plume allows the detection of the momentum flux exiting the single hole and, under appropriate hypotheses, the evaluation of the corresponding mass flow rate time-profile. In this paper two methodologies for the hole-specific flow rate evaluation, both based on the spray momentum technique, were applied to two different GDI nozzles, one featuring equal hole dimensions and one with two larger holes. Three different energizing times at 100 bar of fuel pressure were tested in order to cover a wide range of operating conditions.
The results were validated in terms of injected mass by means of a proper device able to collect and weigh the fuel injected by each single nozzle hole, and in terms of mass flow rate using a Zeuch-method flow meter as reference.
Both the proposed methodologies showed an excellent accuracy in the fuel amount detection with percentage error lower than 5% for standard energizing times and lower than 10% for very short injections working in ballistic conditions.
The mass flow rate time-profile proved a good accuracy in the detection of the start and end of injection and the static flow rate level.

INTRODUCTION

Direct injection technology, coupled with down-sizing and boosting, ensures a great improvement of the spark-ignition engine efficiency, reducing the carbon emissions [1]. In the GDI (Gasoline Direct Injection) engine the fuel has a reduced time-window, compared to port fuel injection, to mix with air and evaporate. The spray droplets sizing and the fuel distribution in the combustion chamber are thus the key parameters to drive the mixture formation. The spray sizing can be improved by increasing the injection pressure [2], [3], [4], [5] or exploiting the flash-boiling phenomenon [6], [7], [8], [9]. Solenoid multi-hole injectors are nowadays the standard technology for GDI engines because they ensure high flexibility. By modifying the nozzle geometry (position, direction, length and diameter of the holes) it is possible to match the fuel spray to the combustion chamber in order to optimize the mixture formation [10], [11]. Usually the nozzle holes have the same diameter and so the same flow rate, but in recent years OEMs are introducing injector nozzles featuring holes with different diameters in order to further improve the fuel distribution and thus the mixture formation quality.

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In order to fully exploit the potential of differentiated holes an accurate diagnostic system, able to measure the individual flow rate of each hole, is mandatory. Nevertheless, at the state of the art, a robust and standardized measurement technique is still missing. Conventional flow-meters used for fuel injector diagnostic are based on Bosch [12] or Zeuch [13] method and both allow only the measurement of the whole nozzle.

The spray momentum technique is an established and reliable measurement based on the detection of the spray impact force that allows the evaluation of the momentum flux exiting each hole of a multi-hole nozzle [14]. Momentum flux is an important spray parameter which can be correlated to cavitation inside the nozzle hole [15], spray penetration [16] and mass flow rate [17]. This technique is applicable to the single plume and so can be used to evaluate the individual hole flow rate.

In some work available in literature the spray momentum was already used to measure the hole-to-hole flow rate but most of them are about Diesel injectors [18], [19], [20], [21], [22] and a robust validation of the methodology is missing. In [17] a GDI injection rate test rig based on spray momentum was proposed but only for the whole nozzle measurement.

In this paper two different methodologies are presented, both based on the spray impact force measurement but differing in some basic assumptions and in the evaluation procedure. The first methodology was already published in [23].

Two GDI injectors were tested at 100 bar of fuel pressure and for three energizing times (from small to long actuations, respectively). The first injector (INJ#1) was a standard three-holes nozzle with the same hole size, while the second injector (INJ#2) featured differentiated holes.

The results were validated in terms of both mass flow rate time-profile, using a conventional Zeuch flow-meter, and in terms of injected quantity by means of a dedicated device able to collect and weight the fuel form each hole. The validation process allowed evaluating the accuracy of the proposed methodologies.

The results showed a satisfying accuracy with percentage error lower than 5% for medium and long energizing times and lower than 10% for short injections. The two methodologies were finally compared revealing that one is more fitting for the dynamic mass flow rate measurement while the other is better for the injected quantity evaluation.

THEORETICAL BACKGROUND

As reported in [14] the impact force against a flat surface orthogonal to the injector axis is equal to the momentum flux exiting the nozzle hole. Although the impact force method requires the steady-flow condition, it was demonstrated to provide accurate results also during the transient phases [24] with a proper tuning of the measuring parameters (target diameter and distance from the nozzle) [25].

The impact force signal F can be thus considered equal to the jet momentum flux $\dot{M}$ exiting the nozzle hole during the whole injection duration (1) and the time-integral of the force signal is equal to the spray momentum M (2).

$$\dot{M}(t) = F(t) \tag{1}$$

$$M = \int F\, dt \tag{2}$$

The momentum flux $\dot{M}_i$ and the mass flux $\dot{m}_i$ exiting the nozzle can be expressed by (3) and (4), with ρ being the fuel density, A the effective cross-sectional area, and v the effective exiting velocity. Equations (3) and (4) are valid both for the single hole, indicated by the subscript *i*, and for the whole nozzle, indicated by the subscript *tot* as in equations (5) and (6).

$$\dot{M}_i = F_i = \rho\, A_i\, v_i^2 \tag{3}$$

$$\dot{m}_i = \rho\, A_i\, v_i \tag{4}$$

$$\dot{M}_{tot} = F_{tot} = \sum \dot{M}_i = \rho\, A_{tot}\, v_{tot}^2 \tag{5}$$

$$\dot{m}_{tot} = \sum \dot{m}_i = \rho\, A_{tot}\, v_{tot} \tag{6}$$

The first tested method, here called IM (Integral Method), was already presented in [23]. It is based on the correlation between the total injected mass m_{tot} and the total momentum $\int \mathrm{F}_{tot}\ dt$. The mass flux from each hole $\dot{m}_i$ is evaluated as the respective momentum flux multiplied by the correlation factor *K*, according to the (8), and the injected mass by integrating the mass flux over the time (9).

$$K = \frac{m_{tot}}{M_{tot}} = \frac{m_{tot}}{\int (\sum F_i)\, dt} \tag{7}$$

$$\dot{m}_i = K\, F_i \tag{8}$$

$$m_i = \int \dot{m}_i\, dt \tag{9}$$

The input data for the IM are the total injected mass m_{tot} and the impact force signals F_i.

The second proposed methodology, called SFM (Steady-Flow Method) requires the measurement of the mass flux and momentum flux during the steady-flow phase.

From equations (1) and (3), velocity v_i is proportional to the square root of the impact force (10).

$$v_i = \sqrt{\frac{\dot{M}_i}{\rho\, A_i}} = \sqrt{\frac{F_i}{\rho\, A_i}} \tag{10}$$

Combining equations (4) and (10), mass flux can be expressed as in (11), where the discharge area A_i is the product of the geometric hole area A_{0_i} and its vena contraction coefficient C_{A_i}.

$$\dot{m}_i = \sqrt{\rho\, A_i F_i} = \sqrt{\rho\, C_{A_i}\, A_{0_i} \mathrm{F}_i} \tag{11}$$

The SFM assumes that the coefficient C_{A_i} is the same for each hole and equal to the total one (namely $C_{A_{tot}}$), representative of the whole nozzle. Considering the total quantities during the steady-flow phase, $C_{A_{tot}}$ can be expressed by the (12), where $\overline{F_{tot}}$ is the nozzle steady-state momentum flux and $\overline{\dot{m}_{tot}}$ is the nozzle steady-state mass flow rate.

$$C_{A_{tot}} = \frac{\overline{\dot{m}_{tot}}^2}{\rho\, A_{0_{tot}}\, \overline{F_{tot}}} \cong C_{A_i} \tag{12}$$

Then, via (11), the dynamic mass flux of the *i-th* hole can be evaluated as in equation (13).

$$\dot{m}_i(t) = \sqrt{\rho\, C_{A_{tot}}\, A_{0_i}\, F_i} \tag{13}$$

The injected mass m_i is finally calculated integrating $\dot{m}_i$ over the injection time (14).

$$m_i = \int_0^{T_{inj}} \dot{m}_i\, dt \tag{14}$$

The input data for the SFM are the impact force profiles F_i, the static mass flow rate $\dot{m}_i$ and the hole geometric areas A_{0i}.

EXPERIMENTAL SETUP

Injectors

The proposed methodology is applied to two research, three-hole nozzles, hereafter defined as INJ#1and INJ#2. INJ#1 features with three equal-sized holes; INJ#2 is characterized by a n overall identical spray targeting but with differentiated nozzle hole diameters with two holes (hole#2 and hole#3) with cross-sectional area 24% higher than hole#1. The nozzles were tested at a unique injection pressure of 100 bar and with three different electrical pulse widths (short=0.26 ms, medium=0.60 ms and long=1.0 ms), in order to be representative of the injector operating range. The experiments were carried out using *n*-heptane as test fluid.

TABLE 1– Hole areas, with respect to hole#1, for the analyzed injectors.

Injector	**hole#2** flow area (nominal)	**hole#3** flow area (nominal)
INJ#1	equal to hole#1	equal to hole#1
INJ#2	+24% respect of hole#1	+24% respect of hole#1

Impact Force Acquisition

The pressurized fuel was supplied by the Loccioni Thor static pressure generator and the injection pressure at the injector inlet was detected by a Kistler 4065 piezo-resistive transducer. The injector tip was mounted on a dedicated positioning system that permitted the force sensor (Kistler 9215) to rotate around the injector tip in such a way to position it orthogonally to each plume (FIGURE 1). Being the precise positioning of the force sensor critical, the correct alignment was verified by a Vision Research Phantom Miro M 310 high speed camera. The impact of the spray on the target surface was recorded to check the correct position and the absence of interference with the neighboring jets, as reported in FIGURE 2. The target diameter was 8 mm and it was placed at 8 mm from the nozzle tip. As discussed in [25], the target size and its distance from the nozzle are important parameters to set in order to optimize the force signal output. In this case the 8 mm distance ensures the non-interference among the plumes and the 8 mm diameter ensures that all the jet is entirely intercepted by the target.

For each tested condition the force signal is acquired at 200 kHz by a National Instrument acquisition system, filtered with an 8 kHz Bessel low-pass filter and averaged over 200 consecutive shots.

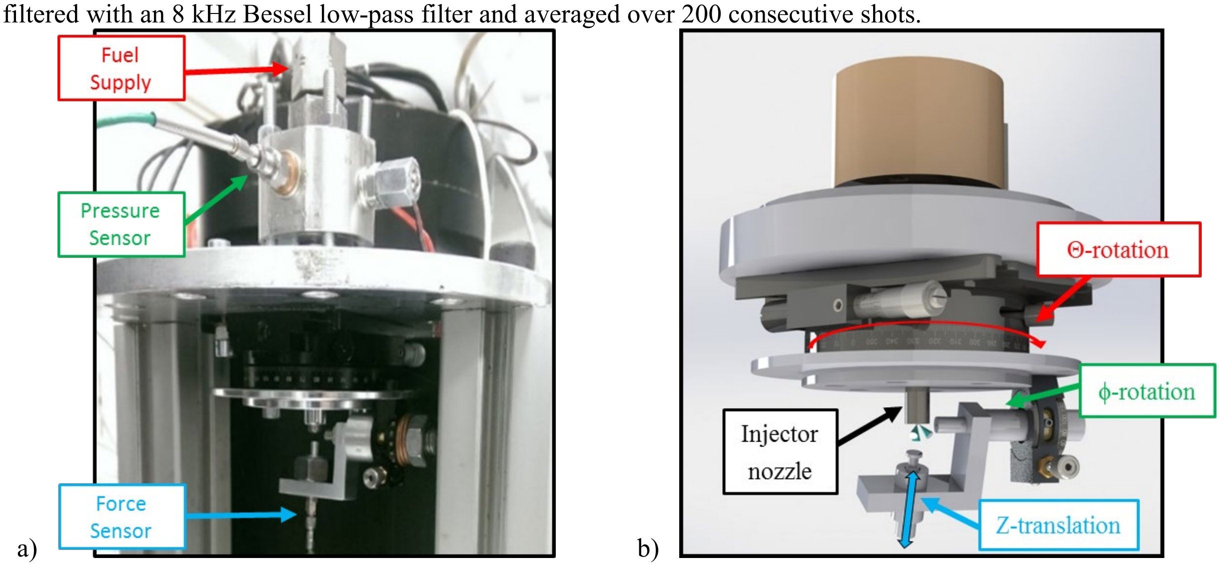


FIGURE 1 – Experimental test bench (a) and description of the positioning system (b).

FIGURE 2 - A frame extracted from the high-speed video used to check the correct positioning of the force sensor.

Total Mass Flow Rate

Measurements of total injection rate used for the validation of the proposed methods were performed by means of the UnigPG Injection Analyzer, a self-developed injection rate meter based on the Zeuch's Method [26]. The injector is mounted in a typical constant volume measuring chamber. When operated, it delivers a certain volume of fuel ΔV into the chamber, increasing its internal pressure of ΔP. After each single actuation, a fast electro-valve is opened, discharging the fuel and restoring the original pressure before the following injection.

Relationship between volume rate and chamber pressure rise over the time expressed by equation (16) is derived from the definition of the fuel bulk modulus (15). As the mass flow rate $\frac{dm}{dt}$ is equal to the volume rate $\frac{dV}{dt}$ multiplied by the fuel density ρ (assumed as constant during the injection event), a relation between mass flow rate and pressure variation over the time is achieved (17).

$$\beta = V_0 \frac{dP}{dV} \tag{15}$$

$$\frac{dV}{dt} = \frac{V_0}{\beta}\frac{dP}{dt} \tag{16}$$

$$\frac{dm}{dt} = \rho\frac{dV}{dt} = \rho\frac{V_0}{\beta}\frac{dP}{dt} \tag{17}$$

$$\frac{V_0}{\beta} = \frac{\Delta V}{\Delta P} \tag{18}$$

The bulk modulus of a given fluid is significantly influenced by both temperature and pressure and its variations cannot be easily determined. To overcome this limitation, the instrument is able to continuously calibrate the $\frac{V_0}{\beta}$ ratio. In fact, fuel discharged from the instrument chamber flows through a Coriolis mass flow meter ("Sitrans CF 2100" supplied by SIEMENS) able to measure the mean injected mass and the fuel density and thus providing the injected volume ΔV. If chamber pressure increase Δp is known, $\frac{V_0}{\beta}$ can be determined using equation (18).

At each operating condition, after a proper thermal stabilization, the acquisition procedure is repeated for 300 consecutive shots, in order to evaluate the average injection rate curve, the mean injected mass and the shot-to-shot variability. Similarly to traditional mass flow meters, the injector works in a discharging ambient filled with fuel at a base pressure of 5 bar.

As the impact force is acquired with a back-pressure equal to the atmospheric one, the same pressure drop (equal to 100 bar) is kept for both the experiments, in order to ensure the consistency of mass flow rate and impact force measurements. Moreover, the absence of significant cavitation phenomena moving the back-pressure from 1 bar up to 5 bar is verified. The absence of significant cavitation effects makes the different measurement techniques (Zeuch for the mass flow rate and impact force method for the momentum flux) comparable, even if performed at different back-pressures.

The injection rate profiles of the two tested injectors at 100 bar are reported in FIGURE 3. These signals were used as reference for the mass flow rate validation and the static flow rate used in the SFM was obtained from the longer injection rate profile cut between 0.4 and 1.2 ms from the electric start.

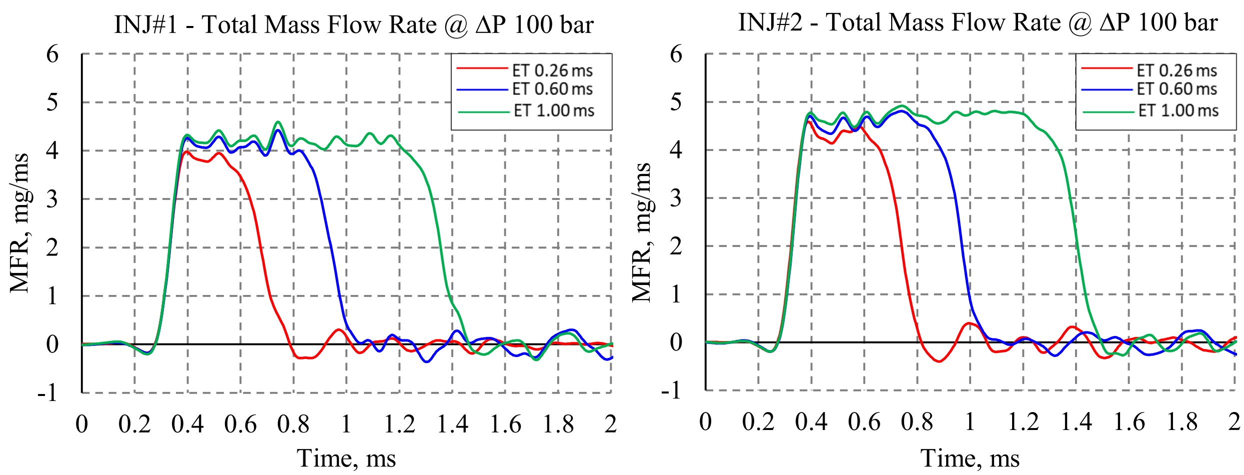


FIGURE 3 - Global injection rates of investigated nozzles for an injection pressure of 100 bar and different energizing times.

Injected Quantity Validation System

Using the same positioning system of the force sensor, a micro-tube was placed in front of each hole and fuel injected by the hole was collected and weighed for 2000 consecutive shots. The micro-tube positioning was aided by the previously described high speed camera and two frames of the spray entering the collecting tube are reported in FIGURE 4 to prove both the correct tube positioning and the absence of plume-to-plume interference.

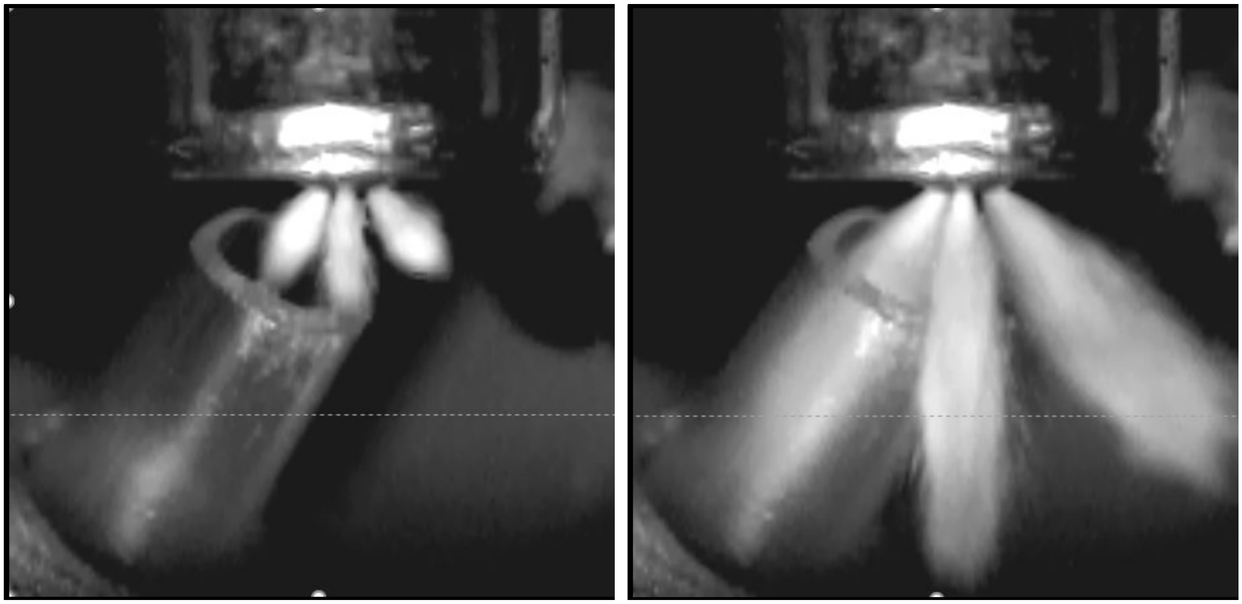
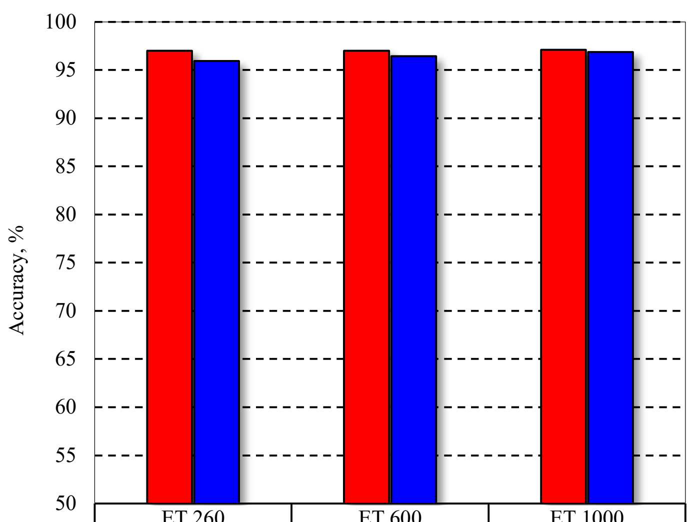


FIGURE 4 – Two different frames of the collecting process by the micro-tube during injection.

The collecting device capability was verified evaluating its accuracy as in equation (19), where $m_{TOT\,weighed}$ is the total mass delivered by the nozzle measured through a global collecting and weighting procedure, while $m_{i\,collected}$ is the mass injected from the *i-th* hole and measured by the proposed collecting device.

$$accuracy\% = \left(1 - \frac{\left(m_{TOTweighed} - \sum_{jets} m_{i\,collected}\right)}{m_{TOTweighed}}\right) * 100 \tag{19}$$

The results reported in FIGURE 5 show a satisfying accuracy, with values higher than 95%. Main error sources could be the evaporation of the injected fuel as well as the liquid film formed on the micro tube; however, the large number of collected shots reduces the impact of error sources ensuring elevated accuracy of the experimental apparatus.



	ET 260	ET 600	ET 1000
INJ#1	97.01	97.01	97.10
INJ#2	95.94	96.42	96.86

FIGURE 5 - Collecting device accuracy.

EXPERIMENTAL RESULTS

The mass flowrate profile of each hole was obtained by processing the impact force measurements according to the methods descripted above. The results are reported in FIGURE 6. In each graph of FIGURE 6 the mass flow rates of the three holes are plotted. For each injector nozzle and each energizing time the results obtained by the two methods are reported (IM purple frames and SFM green frames in FIGURE 6).

A first comparison between IM and SFM showed that the results processed via the IM presented higher flow rate values and shorter event duration for all the tested conditions.

Hole#1 evidenced flow rate levels higher than expected; in fact it should be equal to the other holes for INJ#1 and 24% lower for INJ#2. The central position and quasi-axial orientation of hole#1 can justify its higher discharge coefficient and thus its higher flowrate. Due to the method assumptions, the SFM should be more able to capture the hole-to-hole variation of the discharge coefficient and should give more accurate results.

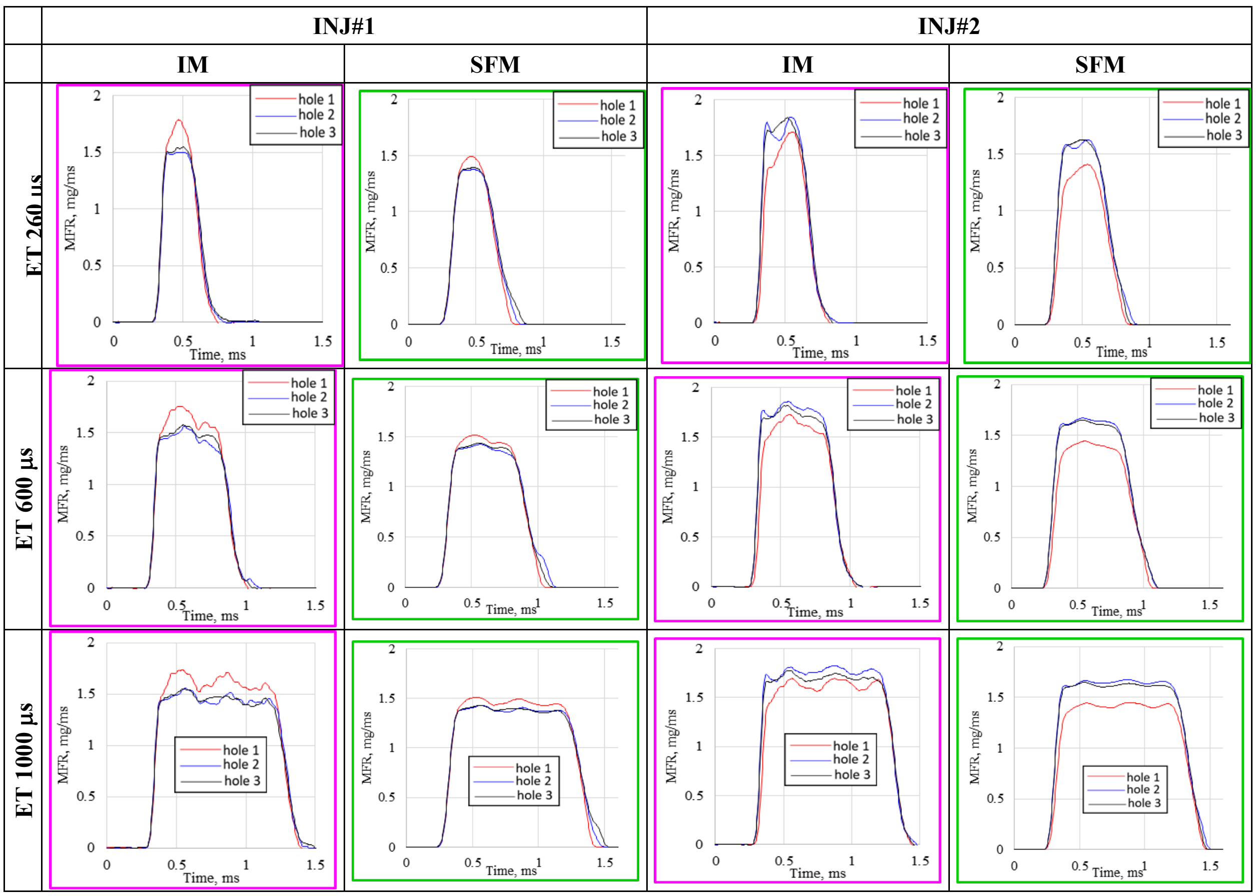


FIGURE 6 – Single-hole IR curves for the analyzed nozzles and different ET durations, estimated via the proposed methods (IM left, SFM right).

Total Mass Flow Rate Validation

FIGURE 7 shows the validation of the proposed methods in terms of total mass flow rate curves, obtained as the sums of the contributions of the single holes, with the reference signals measured by the Zeuch instrument (FIGURE 3). In each graph of FIGURE 7 the reference curve (dashed black) is compared with the results from IM (purple plot) and SFM (green plot). The signals from IM and SFM were shifted in time in order to compensate the delay introduced by the "fly time" that the spray spends from the nozzle hole to the target.

The SFM showed a perfect detection of the injection start, while the IM was slightly delayed. Looking at the longer injection, the SFM is very accurate in the detection of the static flow level, while the IM is overestimated in all conditions. also in the end of injection SFM evidenced better performances than IM with lower error, even if both the methods tends to advance the injection end.

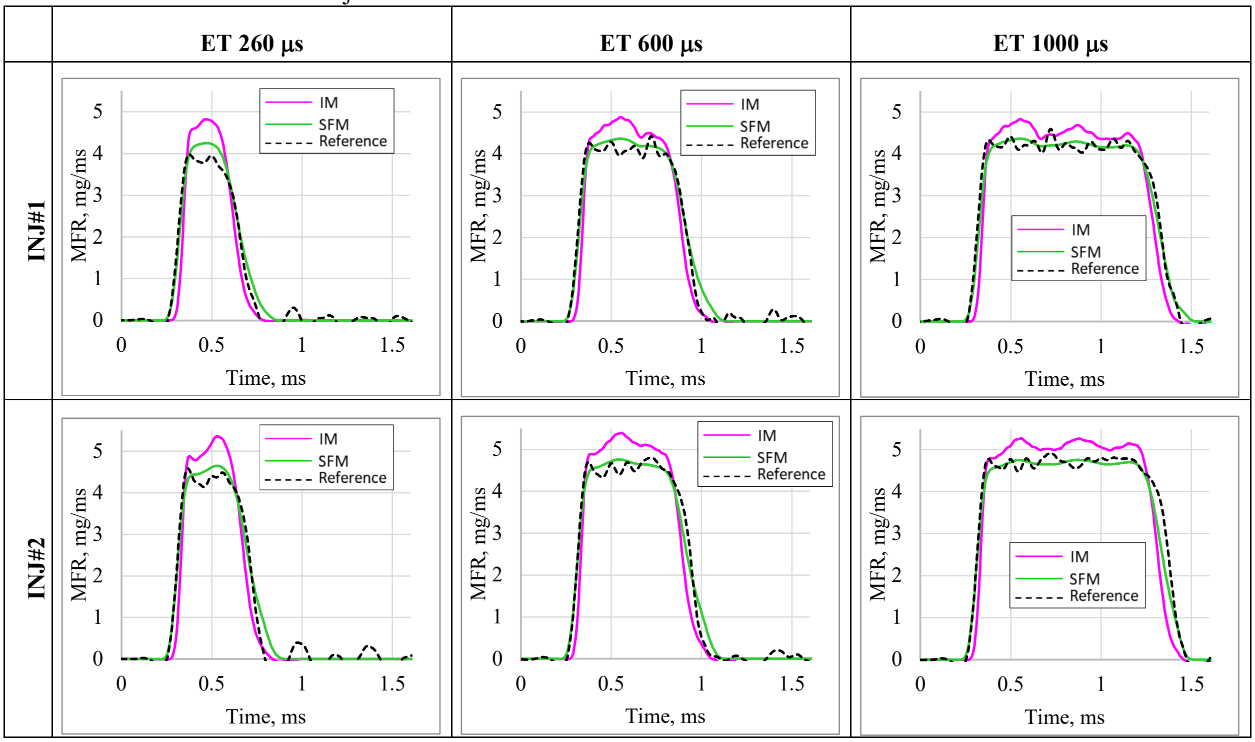


FIGURE 7 – Total mass flow rate validation: IM (solid purple) SFM (solid green) and reference signal from Zeuch flow-meter (dashed black lines).

Injected Mass Validation

The second step of validation focuses on the injected masses of each nozzle hole, calculated as the time-integral of the mass flow rate curves reported in FIGURE 8 for IM (first row) and SFM (second row). The injected mass measured with the collecting device was used as reference. For medium and longer injections both the proposed methods showed similar results, with percentage error lower than 5%. For the shortest injection the IM showed better results with the error still lower than 5%. The SFM was less accurate for small injections with a 9.5% error peak.

It is important to highlight that the injected quantity analyzed during the test campaign were very small, ranging from 0.4 mg/shot to 1.45 mg/shot for the longer injection. Therefore a 5% error corresponds to an absolute error of 0.02 mg/shot for the shortest injection and 0.07 mg/shot for the longer injection. In addition, the shortest injection is operated in ballistic conditions, with the needle that does not attain its maximum lift. It is a very transient signal that is challenging for the impact force acquisition.

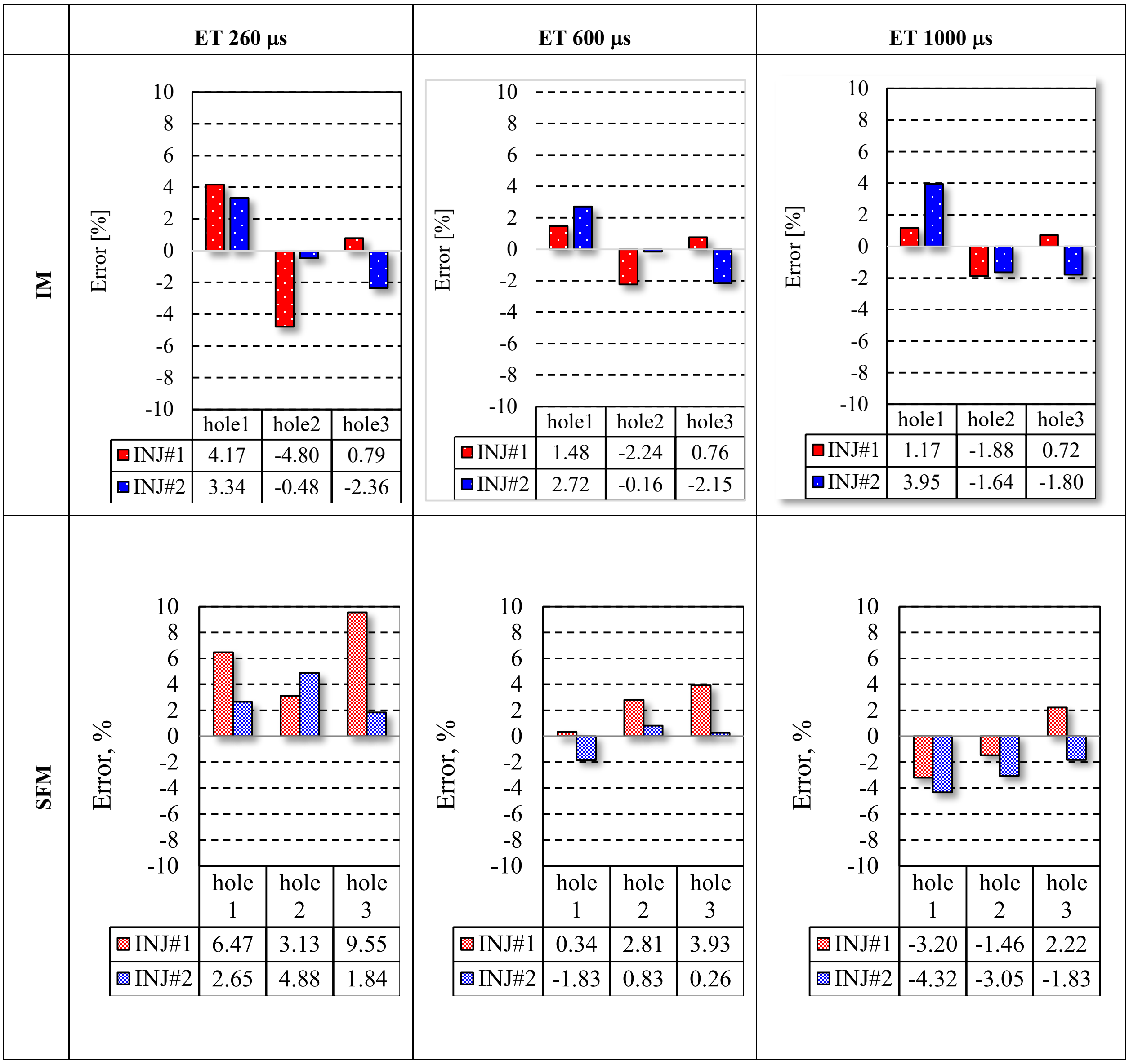


FIGURE 8 – Validation of the single- hole injected mass for ET equal to 260 µs (left), 600 µs (middle) and 1000 µs (right). Percentage error for IM first row) and SFM (second row).

CONCLUSIONS

The mixture formation plays a fundamental role in GDI engines due to the limited time available for the entire combustion process. The fuel injector is the key component for a correct mixture formation and the multi-hole type is nowadays the standard in virtue of its flexibility and capability to match with the combustion chamber and swirl/tumble motion. In order to improve this flexibility, OEMs are developing fuel injector nozzles with differentiated hole diameters. For this kind of components a precise knowledge of the flow rate hole-to-hole is required. Nevertheless, a robust diagnostic technique is still missing because commercial flow-meters can only measure the entire nozzle flow.

In this paper two single jet flow measurement methodologies, called Integral Method (IM) and Steady Flow Method (SFM) and based on the impact force measurement, were presented and discussed. The proposed methods were applied to two GDI nozzles, one featuring equal-size holes and one differentiated-size holes nozzle, in order to evaluate the capability of the proposed methods to capture the differences among the nozzle holes.

The methodologies were validated in terms of injection rate comparing the sum of the flow rates from the holes with the total nozzle flow rate measured by means of a conventional Zeuch-method flow-meter. The SFM showed better results in terms of flow rate profile during the injection process transients, with a better detection of start and end of injection and of the static flow level.

The methodologies were also validated in terms of hole-to-hole injected mass, using as reference a dedicated device able to collect and weight the fuel delivered by each nozzle hole. Comparing the injected mass results with the reference values it was possible to evaluate the error introduced by the proposed methods. For long and medium injections (energizing time 1000 and 600 μs) both the methods showed similar performances with the percentage error lower than 5%. With the shortest injection (260 μs) the IM showed better results, in line with the other longer energizing times (error lower than 5%). With the SFM the error grows with very short events up to 9.5% in the worst case. In the analyzed conditions the injected mass per hole was very small (from 0.4 to 1.45 mg/shot), so the absolute error is very small being in all the cases lower than 0.1 mg/shot.

In order to further consolidate the proposed methodologies, both SFM and IM will be applied to the analysis of nozzles featuring a higher holes number and more sophisticated design, in different operating conditions including higher injection pressure levels along with sub-atmospheric and pressurized downstream conditions. Additional efforts will be devoted to the development of an automated fuel collecting device to weigh the mass injected by each single hole.

DEFINITIONS/ABBREVIATIONS

A	Effective cross-sectional area
A_0	Geometric cross-sectional area
C_A	Vena contraction coefficient
CFD	Computational Fluid Dynamics
CMOS	Complementary Metal-Oxide Semiconductor
ET	Energizing Time
F	Impact force
GDI	Gasoline Direct Injection
IM	Integral Method
kfps	kiloframe per second
m	Injected mass
$\dot{m}$	Mass flow rate
$\dot{M}$	Momentum flux
MFR	Mass Flow Rate
SFM	Steady-Flow Method
T_{inj}	Injection duration
v	Fuel effective velocity at the hole exit
WLTP	Worldwide harmonized Light vehicles Test Procedure
IR	Injection Rate
ρ	Fuel density

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