

Experimental Assessment of a Novel Instrument for the Injection Rate Measurement of Port Fuel Injectors in Realistic Operating Conditions

Lucio Postrioti
Universita degli Studi di Perugia

Giulio Caponeri
Università degli Studi di Perugia

Giacomo Buitoni
Shot-to-Shot Engineering

Nic Van Vuuren
Continental Automotive Systems US Inc.

ABSTRACT

In the present paper an innovative approach for the shot-to-shot hydraulic characterization of low pressure injection systems is experimentally assessed. The proposed methodology is an inverse application of the Zeuch's method, which in this case is applied to a closed volume upstream the injector instead of downstream of it as in conventional injection analyzers. By this approach, the well-known constraint of having a finite volume pressurized with the injected liquid downstream the injector is circumvented. As a consequence, with the proposed instrument low pressure injectors - such as PFI, fed with gasoline or water, SCR injectors - can operate with the prescribed upstream-downstream pressure differential. Further, the injector can spray directly in atmosphere or in any ambient at arbitrary pressure and temperature conditions, allowing the simultaneous application of other diagnostics such as imaging, momentum flux measurement or sizing instruments.

The developed instrument - named dINJ - is designed for the simultaneous measurement of both global injected quantity and injection rate time-history over a statistically significant basis of consecutive events, thus obtaining a complete hydraulic characterization of the tested injector.

In this paper, the proposed experimental approach is introduced and discussed. The validation process was carried out by comparing the dINJ instrument injection rate with the corresponding quantity obtained by a conventional injection analyzer during simultaneous hydraulic tests. During the validation phase, the abnormal low pressure injector operation caused by conventional injection analyzers occurs. The same injector was then characterized by the standard dINJ configuration evidencing the proposed approach capabilities.

CITATION: Postrioti, L., Caponeri, G., Buitoni, G., and Van Vuuren, N., "Experimental Assessment of a Novel Instrument for the Injection Rate Measurement of Port Fuel Injectors in Realistic Operating Conditions," *SAE Int. J. Fuels Lubr.* 10(2):2017, doi:10.4271/2017-01-0830.

INTRODUCTION

In the current automotive scenario, Gasoline Direct Injection (GDI) technology is quickly spreading in several markets due to its higher potential in the fulfillment of stringent CO₂ emission regulations. In the same time, the more conventional Port Fuel Injection (PFI) technology is still being developed for those applications for which the reduced vehicle mass and/or less rigorous fuel conversion efficiency targets are to be achieved. Further, different low pressure injection applications are gaining attention such as auxiliary fuel injection systems combined with GDIs, water and urea-water solution (UWS) injection systems. Water injection is considered a promising technique [1] to control the actual inlet charge temperature in spark ignition engines, thus enabling

the adoption of very high compression ratio levels to improve thermal efficiency. UWS injection systems are widely used to introduce ammonia in Diesel engines exhaust lines as reducing agent for SCR systems in NOx emission abatement systems [e.g. 2].

The injector operation accuracy and repeatability are crucial for any kind of low pressure injection system, raising the need for an accurate shot-to-shot measurement of the global injected volume. This measurement should be carried out in realistic operating conditions in terms of upstream and downstream pressure levels and actuation frequency. Further, even if the injection rate time-history is not considered not crucial for PFI engines and low pressure injectors, the

detection of the actual discharge time-history could significantly assist in the development and fault-analysis of low pressure injectors, e.g. enabling the identification of dispersions in the opening/closing transients or bouncing phenomena.

Unfortunately, the actual operation of low pressure injectors is difficult to measure by commercially available Injection Analyzers (IAs) which are normally designed in order to capture the injection rate profile and/or the shot-to-shot injected quantity for Diesel and GDI injectors. The main limitations in using conventional IAs with low pressure injectors are related to the need of applying a significant counter-pressure downstream the injector, typically in the range 5 to 10 bar [3, 4, 5, 6, 7, 8]. This implies a significant modification for low pressure injectors operation with respect to standard conditions. Further, in the closed-vessel or pipe type instruments, the fuel injection process causes a significant downstream pressure rise which is typically considered negligible for Diesel and acceptable - but somehow a limitation - for GDI systems. The measurement ambient pressure rise in conventional IAs is clearly unacceptable for low pressure systems, as it dramatically tends to reduce the injection rate during the discharge process. Finally, as for GDI and Diesel injectors, the use of conventional IAs to measure the injection rate prevents any contemporary analysis of the resulting spray in terms of imaging or drop sizing/velocimetry.

In the present paper, a novel injection analyzer named dINJ specifically developed for low pressure injectors is assessed in comparison with a conventional Zeuch's Method-based IA. The proposed instrument is based on the detection of the pressure time-history in a closed vessel acting as isolated fuel rail during the injection process. The PFI injects in an ambient pressure vessel, preserving its standard upstream/downstream pressure operating conditions and allowing the application of diagnostics for the resulting spray analysis, while the upstream vessel is designed in order to minimize the pressure fall during the discharge process. At the end of the injection process, a synchronized, fast acting valve is used to restore the target rail/vessel pressure for the next injection process. By the proposed instrument, the shot-to-shot injected quantity and injection rate time-profile can be determined.

EXPERIMENTAL SETUP

Nowadays, the most diffused instruments used for the hydraulic analysis of injection systems are based on or derived by the so-called Bosch-type [5] or/and Zeuch's Method [2, 6]. Both these types of instruments are characterized by the presence of a closed volume (measuring chamber or pipe) downstream the injector. For the correct instrument operation a minimum pressure level inside the closed volume is prescribed, often in the range 5 to 10 bar. This boundary condition is normally considered correct for Diesel injection systems, while it causes some limitations for GDI systems in terms of operating conditions range, e.g. the hydraulic analysis in sub-atmospheric counter pressure conditions is impossible.

Basically for the same motivations, the use of conventional IAs for the analysis of low pressure injectors is unacceptable; the following main issues can be identified:

- the need for a high counter pressure level represents an artificial boundary condition for low pressure injectors, that can be compensated at the start of the injection process by an increased injection pressure; this implies drawbacks in terms of altered flow conditions as a liquid jet in a liquid medium is produced.
- The small measuring chamber volume normally causes a further significant counter pressure increase during the injection process, which tends to decrease the initial pressure differential across the injector. Consequently the instantaneous flow rate is progressively reduced during the injection event. This phenomenon is particularly evident for long actuation times, for which the injected volume is significantly reduced with respect to standard operation. Also for GDI systems, the measuring volume pressure rise can put some limitations to the hydraulic analysis for moderate injection pressure levels and large injected volume conditions.
- As for Diesel and GDI systems, any kind of simultaneous spray analysis (e.g. imaging or momentum flux) is impossible.

Globally, in order to correctly investigate the hydraulic behavior of low pressure injectors, it is mandatory to remove the artificial boundary condition given by over-atmospheric pressure level downstream the injector. To accomplish this task, an innovative instrument has been conceived basing on the know-how gained at SprayLAB-University of Perugia with the development of a proprietary injection analyzer based on the conventional application of the Zeuch's method [10, 11, 12].

The novel instrument - named dINJ Injection Analyser ¹ - features the ability to measure the injection rate and injected mass (resolving the shot-to-shot dispersion) regardless the backpressure conditions. The proposed instrument is currently used for the hydraulic analysis of low pressure injection systems such as PFI and SCR, while the application to GDI systems is currently under development.

The dINJ injection analyzer can be defined as an inverse or upstream application of the Zeuch's method. In the following [Figure 1](#), a schematic of the proposed dINJ injection analyzer is reported.

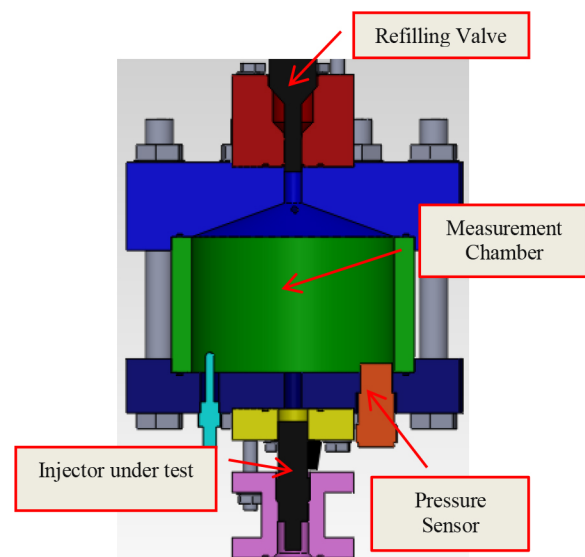


Figure 1. Schematics of the dINJ Injection Analyzer

¹ patent pending

A closed vessel or measuring chamber acts as an isolated rail feeding the injector, that can operate against the atmosphere or any given ambient condition from vacuum to high pressure conditions. In fact, according to this scheme the detection of the downstream pressure conditions is not required for the injection rate/injected volume evaluation. The injection rate and the injected quantity measurements are based on the analysis of the pressure time-history in the measurement chamber. The application of the Zeuch's method to the measurement chamber during the injection event allows the evaluation of the out-flow rate, corresponding to the tested injector injection rate:

$$\frac{dm}{dt} = \rho \frac{V}{\beta} \left| \frac{dP}{dt} \right| \quad \text{Eq. 1}$$

$$\Delta P = \frac{\beta}{V} \Delta V \quad \text{Eq. 2}$$

Here m is the fuel mass, ρ and β are the fluid density and bulk modulus, V and P are the measurement chamber volume and pressure respectively. ΔV is the volume globally injected during the injection event and ΔP is the corresponding chamber pressure decrease. In designing the instrument, a proper compromise must be attained for the measuring chamber volume V . In fact, in order to obtain a realistic operation for the tested injector, the measurement chamber volume V should be large enough to limit the pressure decrease ΔP during the injection event. At the same time, the same volume V should not be too large in order to improve the instrument sensitivity for small injected quantities. At the end of each injection event, a fast acting refilling valve is used to restore the chamber pressure level for the next injection event. In the following Figure 2, a time-history plot for a two consecutive injections sequence is reported to clarify the instrument operation; positive values for the injection rate correspond to the actual injection processes, while negative values correspond to the chamber refilling phase.

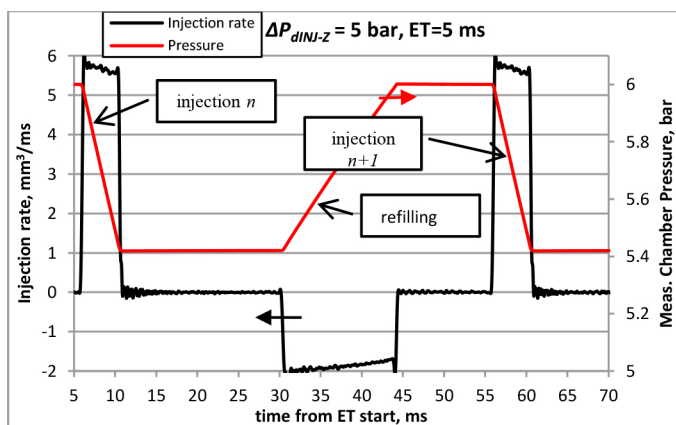


Figure 2. Consecutive injection events (Inj. Freq. 20 Hz) - chamber pressure and injection rate profiles.

According to the proposed scheme, the injector can operate in realistic mode against a constant pressure downstream ambient being fed by a reasonably constant pressure volume: in Figure 2 the rail

pressure decrease is 0.6 bar with 24.5 mm³/shot injected volume. The potential to investigate peculiar operating conditions such as flash boiling is preserved; further, the simultaneous spray analysis by optical or non-intrusive approaches can be performed. With the current dINJ design for low pressure injection systems, the refilling phase is accomplished in less than 15 ms (depending on the upstream and downstream pressure levels), allowing injection frequencies up to 40 Hz. The shot-to-shot dispersion of the measuring chamber pressure before the injection event (*i.e.* the injection pressure dispersion) is lower than ± 0.025 bar.

The dINJ Injection Analyzer control software is designed to simultaneously measure both the injected mass and the injection rate time history in a given operating condition. The operating condition is defined by the injection pressure level, by the downstream ambient pressure/temperature and by the injector actuation strategy (injection frequency, energizing time ETs and dwell times DTs for multiinjection strategies). The mean injected mass and the dynamic signals (*e.g.* measuring chamber pressure and solenoid current) are acquired in the same batch of consecutive injection events, according to the following global procedure:

- **Warm-up:** in order to achieve a proper thermal stabilization and air evacuation, a proper warm-up period is applied with the injector actuated in a given operating condition;
- **Mean injected mass evaluation** - A batch of injection cycles (*e.g.* 1000) with a given injector operating condition is executed and used for the mean injected mass measurement, by means of a mass flow meter along the fuel supply line upstream of the measuring chamber. In the current dINJ setup, a Coriolis mass flow meter (Siemens Sitrans CF 2100) is used. The injected mass and density measured over the entire batch of injector actuations are used to compute the mean injected volume (ΔV in Eq. 2). During the same batch of events, the vessel pressure decrease is detected for each single cycle and the corresponding mean value is computed (ΔP in Eq. 2). The resulting β/V mean value for the specific batch of injection cycles is used as a scaling factor to compute the single injection event injected quantity.
- **Injection rate evaluation** - During the same batch of events, for a sub-set of consecutive injections (*e.g.* the last 500 of the 1000), the chamber pressure signals are recorded and analyzed.

The application of Eq. 1 allows the evaluation of the injection rate, using the β/V mean value derived in the above reported step. Following this approach, the problem of evaluating the actual fluid Bulk Modulus (dependent on the fluid composition, pressure and temperature) is circumvented being the β/V ratio evaluated in the specific test conditions.

The signal analysis is resolved in the single injection event hence both the mean behavior and the shot-to-shot dispersion evaluations are possible for the injected volume, for the injection rate and for all the dynamic signals. The repetition of the above described procedure for different ET values (or dwell times in multi-event strategies) can be used to parametrically analyze the effect of each of the quantities defining the injection strategy.