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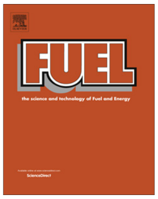

An experimental and numerical analysis of pressure pulsation effects of a Gasoline Direct Injection system

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HIGHLIGHTS

- A complete Wet-System hydraulic bench for Gasoline Injection Systems was setup.
- The actual GDI injector hydraulic behavior when operating in an engine-like system layout was assessed.
- The possible influence of the injection system layout on the rail pressure pulsation and injector operation was investigated.
- A 1D numerical code modeling the entire injection system was tuned and applied to further complete the analysis.
- The injector hydraulic behavior with advanced injection strategies (reduced dwell time) was investigated.

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ABSTRACT

Downsized, turbocharged GDI engines are considered as the most effective system architecture car makers can implement to meet stricter CO_2 production and pollutant emissions regulations. Moreover, the GDI engine is accounted to be the ideal thermal part of hybrid powertrains which will play a more and more significant role to meet future CO_2 and emissions standards. Hence in the last years significant research efforts are being applied to the development of GDI technology in order to optimize its performance in terms of specific fuel consumption and emission control capabilities.

These engines require an extremely reliable high pressure fuel injection system to allow advanced combustion strategies and to improve the fuel atomization process and the air–fuel mixing. Nevertheless, in these installations intense fuel pressure fluctuations may occur due to continuous pumping and injection events, possibly causing low precision in the fuel metering from cylinder to cylinder and relatively poor spray quality. For this reason the injection system design must be supported by accurate computational models able to predict the actual injector flow and the whole fuel system behavior.

This paper describes a combined 1-D numerical and experimental analysis of a complete GDI injection system with a particular focus on the waves propagation phenomena and their dependence on the system geometry, such as high pressure pipe length and internal diameter, rail inlet position, flow-restrictor diameter.

The numerical code was validated through the comparison of the predicted results with experimental data, mainly pressure and instantaneous injected flow rate measured by a hydraulic test bench (named Wet-System) developed at SprayLab – University of Perugia, which consists of the high pressure pump, the pipes, the fuel rail and injectors so to simulate the complete injection system operation. The injection-system mathematical model was then used to predict the system dynamic response in operating conditions beyond the test bench limits, paying specific attention to the flow-restrictor effect. Finally, the model capability in accurately predicting the waves dynamics effects on the injected fuel flow rate and mass was assessed for multi-injection strategies, when the dwell time between consecutive injections is varied.

1. Introduction

The current scenario for the automotive powertrain development is substantially driven by the demand for a drastic reduction

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Nomenclature

Definitions/abbreviations

1-D	one-dimensional
AC	Alternating Current
BDC	Bottom Dead Center
cad	crank angle degree (deg)
CoV	Coefficient of Variation (%)
C_{wall}	wall compliance (Pa^{-1})
DT	Dwell Time (μs)
EMI	Einspritz Mengeindikator (injection quantity indicator)
ET	Energizing Time (μs)
EVI	Einspritz Verlaufindikator (injection curve indicator)
FMV	Fuel Metering Valve
FPGA	Field Programmable Gate Array
GDI	Gasoline Direct Injection
m	fluid mass (kg)
P	pressure (bar)
PID	Proportional–Integral–Derivative
$\dot{Q}$	flow rate (m^3/s)
TDC	Top Dead Center
V	Pipe or chamber volume (m^3)
V_0	Injector Analyzer internal chamber volume
ρ	fluid density (kg/m^3)
β	fluid Bulk Modulus (Pa)

of the specific CO_2 production posed by legislation, along with the on-going decreasing trend for the allowed pollutant emission levels.

In this frame, the most effective way to improve the spark-ignition engine thermal efficiency is the shift from the homogeneous charge, in-direct injection scheme to the stratified charge, direct injection combustion system. Hence, Gasoline Direct Injection (GDI) engines are considerably increasing their market share, often in combination with turbo-charging of small to medium displacement units, in order to exploit the potential of such configured engines to improve thermal efficiency in key operating conditions such as low load and cold start. Further, GDI technology applied to downsized and turbocharged engines represents today the most attractive technological solution for the thermal part of hybrid powertrains.

The quick development of direct injection in spark ignition engines implies a higher importance of the injection system performances in terms of combustion and emissions control. In fact, along with the theoretical advantages, the development of stratified charge, direct injection systems implies a number of issues that must be faced. The fuel metering accuracy, the rate of fuel introduction in the combustion chamber and the consequent spray evolution, fuel atomization and mixing with surrounding air directly control the combustion development. Hence the engine performance and efficiency along with its pollutant emissions and noise are directly affected by the injection system in a wide range of operating conditions. As a consequence, a deep knowledge of the actual injection rate is nowadays crucial for designing new generation injection systems, particularly in the operating conditions in which advanced injection strategies are to be applied to govern the combustion process.

A typical direct injection system consists of a low pressure pump feeding a cam-actuated high pressure pump, a Fuel Metering Valve (FMV) acting as injection pressure regulation system, a pipe connecting the pump to a common rail and the injectors delivering the fuel in the combustion chamber. In the aim of increasing the injection system metering accuracy, the stand-alone injector analysis may be not adequate. In fact, the injector performances are affected by many boundary parameters, such as the pressure time-history upstream the injector, the backpressure, the fluid and injector nozzle temperature. In particular, the upstream pressure time-history is largely influenced by the injection system layout and by its actuation frequency. As well known, fast opening and closing of injectors and alternate motion of the high pressure pump piston produce considerable pressure fluctuations in the fuel system, possibly resulting in an injector behavior in terms of fuel metering and injection rate profiles that can be significantly different from what is predicted by a standard, stand-alone injector characterization [1–9]. Further, pressure fluctuations can result in operation noise and damaging of some components [10]. Hence, the ability in evaluating (both numerically and experimentally) the actual operating conditions for the entire injection system is crucial to obtain robust results.

The Wet System approach is commonly used in order to replicate, in a research test bench, the overall injection system and to control its working parameters. A GDI Wet System test bench was set-up at the SprayLab – Università di Perugia, in partnership with Magneti Marelli Powertrain, for the direct analysis of complete GDI systems and to support the development of numerical tools for the corresponding computational analysis.

This paper describes a combined 1-D numerical and experimental approach applied to the analysis of a three-cylinder GDI system application. A numerical model of the complete injection system built in AMESim environment was validated through the comparison of predicted results with the evidences obtained by the SprayLab Wet System bench. Significant insight into the system layout effects on the injector hydraulic operation in terms of injection rate with single and multiple injection strategies was obtained. Peculiar attention was devoted to the influence of pressure waves propagation phenomena in different operating conditions.

2. The GDI Wet System test bench

The GDI Wet System test bench assembly is show in Fig. 1, with the complete injection system composed by the high pressure pump, the pipe connecting it to the rail and the three injectors.

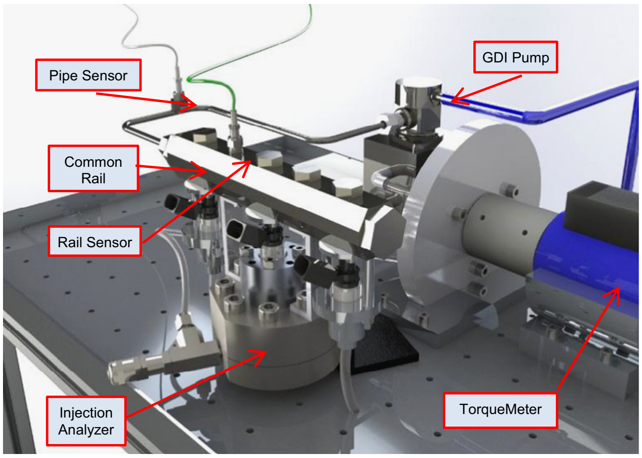

Fig. 1. GDI Wet System test bench layout.