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Split injection in a Homogeneous stratified gasoline direct injection engine for high combustion efficiency and low pollutants emission

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A B S T R A C T

The effects of splitting the injection event in a GDI (gasoline direct injection) engine operating with a HOS (homogeneous stratified) lean charge are analysed through experimental and numerical techniques. Injection is assumed as divided in two parts, each delivering the same gasoline amount, the first occurring during intake, the second during compression.

The work is initially focused on the experimental characterization of the engine under study for the collection of data concerning the in-chamber combustion development. Beside measurements of in–cylinder pressure, UV chemiluminescence is applied to follow the OH radicals formation from spark ignition up to the late combustion phase, thanks to the optical accessibility to the combustion chamber. The collected data serve to the validation of a properly formulated three-dimensional (3D) CFDs model for the simulation of the whole engine working cycle.

The definition of the control strategy leading to the greatest combustion efficiency and lowest pollutants emission is made in two steps through numerical optimization: the 3D CFD model is first run to build a low number of samples to be used within a Gaussian RSM (response surface method) to reconstruct, in the DOE (design of experiments) space, the integral of the in–cylinder pressure over volume in the closed valve period; in the second step, the coupling between the 3D engine model and the Simplex algorithm is performed in a restricted DOE subdomain defined according to the first step analysis. The assessed methodology highlights the synchronization of both spark ignition and split injection leading to the highest power output and the lowest pollutants release. The experimental verification of the numerical findings is finally carried out.

1. Introduction

The worldwide increased motorized mobility and the need for low fuel consumption and reduced exhaust emissions are forcing manufacturers and researchers in the automotive field to the continuous search for improvement solutions to existing technologies. GDI (gasoline direct injection) is surely the most attractive answer to the demand for high energy efficiency of spark ignition engines. The gasoline latent heat of vaporization subtraction from the surrounding environment determines lower in-cylinders temperatures with respect to the PFI (port fuel injection) architecture, reduced tendency to knock and the possibility to adopt higher compression ratios [1,2]. The theoretically estimated reduction of fuel consumption is up to the 25%, depending on the considered system [3–5]. This explains existing projections about the market share of vehicles that even envisage a quote of 25% being earned by the GDI technology by 2020 [6].

GDI has a long history, beginning with its application in 1925 on an aircraft Hesselman engine and the development of the first Bosch injection system for automotive applications in 1952. In recent years, after the release of the first generation direct injection engines of the late nineties, mainly based on the wall-guided concept of mixture formation [2], a second generation started being manufactured and brought to the market from 2006, mainly characterised by an extended range of operation under the so-called stratified mode [7]. The combination of charge stratification with turbo-charging and downsizing was soon recognised as

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representing the biggest potential for reduction of fuel consumption in GDI engines and still constitutes the best available technology for this kind of propulsion system.

Charge stratification is due to late injections that realise a rich zone just in the proximity of the spark plug and leaner zones toward the cylinder walls, for overall lean burn. Stratification reduces fuel consumption at lower loads, while homogeneous charge realized through early injection is needed at higher engine loads and speeds. Leaner gases in correspondence of the walls have also more favourable thermodynamic properties for reduced heat losses. However, if the air-fuel mixture is too lean, the high dilution diminishes combustion stability, with a decrease of flame speed and possible partial burning. Realising mixtures guaranteeing stable gasoline oxidation over the whole engine working map, therefore, is a challenging task that requires sophisticated air-to-fuel ratio feedback control. The consequence is that a variety of high-precision sensors to detect the engine operating condition and a wide range of actuators to better dose EGR (exhaust gas recirculation) and set intake and exhaust valve timing are required. In addition, high-performance and high-pressure gasoline injectors and pump to deliver atomized and optimally shaped sprays that can conform to the specific combustion chamber configuration have to be employed. Time and pressure of injection play a fundamental role in this perspective.

As a counterpart of stratification or air-to-fuel ratio inhomogeneities in the mixture, the formation of pollutants as unburned hydrocarbons and PM (particulate matter) is also to be accounted for [8]. PM has been an issue just in compression ignition engines up to a few years ago, especially for the well-known trade-off with NOx (nitrogen oxides). Each measure aimed at reducing one of the two pollutants is indeed recognised as having a negative effect on the other [9]. The latest European regulations on emissions of light duty passenger cars and commercial vehicles on the NEDC (New European Driving Cycle) have introduced particulate number limits also for GDI engines [10].

PM formation, as previously said, is related to non-uniform distributions of the air-to-fuel ratio within the combustion chamber and the presence of particularly rich zones. This also implies the need to consider possible gasoline deposits in correspondence of walls, where the fuel spray may hit either unintentionally or intentionally. In GDI engines based on the so-called wall-guided mixture formation mode, the piston head is properly shaped in such a way to redirect the impacting droplets towards the spark plug [11]. The deposited film of gasoline over walls makes slower the liquid evaporation and PM likely to originate.

The spray-guided mixture formation mode proves being more suitable to realize stable stratification under various loads and speeds, hence to accelerate gasoline evaporation under late injections, when short times are available for mixture preparation [7]. The spray-guided concept reduces the impact of gasoline droplets with respect to the wall-guided one. This implies favourable effects on HC (unburned hydrocarbons) and PM, which are generally otherwise reduced through advanced injection start, with a consequent reduction in the maximum value of the air-to-fuel ratio and possible combustion instabilities.

Nevertheless, a recent research on PM emission from three types of GDI engines powered vehicles (naturally aspirated wall-guided, turbocharged air-guided, and naturally aspirated spray-guided) over the NEDC, indicates that none of these may satisfy the proposed EURO 6 particle number regulations, unless any measure is pursued between substantial engine hardware modification, improved energy management system calibration or even application of particle filters [12].

Use of split injection [13,14] is a valuable option. Split injection, in fact, besides being a way to increase exhaust gases temperature fastening the catalyst warm-up [15], may induce a reduction of both HC and smoke emissions with higher fuel efficiency at steady state part load operation [16,17].

The most recent combustion concept for GDI engines relies on what are indicated as third generation injection systems, featuring piezo-electrically actuated injectors for low opening retard and more precise fuel delivery that can reach up to five injection events in the same engine cycle [18]. Particularly interesting is the so-called HOS (homogeneous stratified) lean mode, that is a combination of the homogeneous lean and the conventional stratified combustion, with the first injection occurring during intake, so that a homogeneous base mixture is formed, and stratification obtained through a further injection during compression and prior to ignition [19]. This may consist of a single or double dose depending on the point of operation on the engine working map.

The state of the art on the effects of multiple injections in GDI engines is reported in the paper by Wislocki et al. [20]. Apart from very few exceptions, a thermodynamic analysis of the engine working cycle under multiple injections is however missing in the literature. Full descriptions of the physical aspects of fuel atomization, nor qualitative or quantitative analyses of its combustion are found. This work aims at giving a contribution in this sense, namely at demonstrating, through thermodynamic analysis [21], benefits deriving by splitting injection under lean burn operation. A CFD procedure aimed at defining the optimal injection strategy and spark advance is presented.

2. Experimental analysis

2.1. Optically accessible GDI engine and optical apparatus

Experimental tests are performed on a single cylinder research GDI optical engine (whose specifications are given in Table 1) equipped with the head of a commercial turbocharged engine having similar geometrical characteristics (bore, stroke, compression ratio) of the research engine. Crank angle degrees relevant to the valve control strategy are expressed before (B) and after (A) the TDC (top dead centre) or the BDC (bottom dead centre). The head has four valves and a centrally located spark plug, while the combustion chamber configuration is designed for wall-guided operation. A six-hole injector manufactured by Magneti-Marelli, 0.140 mm of hole diameter and solenoid actuation, is mounted in lateral position between the intake valves. An experimental characterization of the gasoline spray, as delivered by the considered injector, was preliminary performed both at the mass flow rate test bench and in an optically accessible vessel to collect necessary data for the assessment of a 3D CFD sub-model of the issuing spray dynamics [22].

Measurements on the engine are performed at 2000 rpm, WOT (wide open throttle) and with commercial 95 RON gasoline, 100 bar fuel injection pressure, relative air-to-fuel ratio $\lambda = 1.1$. This setting corresponds to an injected mass of 22.34 mg/cycle. Intake air temperature is between 300 and 310 K; cooling and lubricant fluid

Table 1
Engine specifications.

Bore × stroke	79 × 81.3 mm
Connecting rod length	143 mm
Valves per Cylinder	4
Compression ratio	10.6
Intake valve opening (IVO)	3° BTDC
Intake valve closing (IVC)	36° ABDC
Exhaust valve opening (EVO)	27° BBDC
Exhaust valve closing (EVC)	0° ATDC
Fuel system	GDI 6 hole nozzle