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Mixture preparation and combustion in a GDI engine under stoichiometric or lean charge: an experimental and numerical study on an optically accessible engine

M. Costa [a,*], F. Catapano [a], P. Sementa [a], U. Sorge [b], B.M. Vaglieco [a]

[a] CNR – Istituto Motori, Viale Marconi, 4, 80125 Naples, Italy
[b] AVL Italia S.r.l., Via Lanzo, 181, 10071 Borgato Torinese (TO), Italy

HIGHLIGHTS

- A combined experimental-numerical study regards an optically accessible GDI engine.
- Stoichiometric and lean mixture formation and combustion are characterized into detail.
- Equivalence ratio inhomogeneity at spark timing is related to un-axisymmetric flame fronts.
- Wallfilm formation is highlighted as contributing to HC and soot emissions.
- Under lean burn, fuel consumption, CO, soot and cyclic variability are reduced by proper control strategies.

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ABSTRACT

In direct injection spark ignition (SI) engines, the spray dynamics and interaction with the surrounding air flow are recognised as strongly affecting mixture quality, combustion development and amount of pollutants released at the exhaust. Spray impact against walls has also to be considered since undesired deposition of liquid as wallfilm causes unburned hydrocarbons and soot formation, hence increased fuel consumption and even augmented cyclic dispersion.

Present work aims at clarifying the dynamics of sprays generated by multi-hole high pressure injectors in the combustion chamber of a gasoline direct injection (GDI) engine, as well as to characterize the combustion development and pollutants formation under various injection modes. Stoichiometric and lean operations are both studied into detail through a combined experimental and numerical approach. Experiments are conducted on an optically accessible engine, whereas numerical simulations are made after the development and validation of a three-dimensional (3D) sub-model reproducing at the best the spray dynamics also in its impact over walls.

Early injection is shown to anyway determine at spark timing slight inhomogeneity in the equivalence ratio distribution of the stoichiometric charge, which makes for the flame propagation being anyway not spherical, but such to exhibit a preferential direction towards the richest zone of the combustion chamber. This leads to the formation of a pocket in the end gases where the knocking phenomenon is likely to occur under some circumstances. Lean charge operation is instead discussed as injection pressure and spark timing are varied to highlight mechanisms of formation of the main pollutants and to define routes for the development of proper engine control strategies. A deep insight in the in-cylinder thermo-fluidynamic processes is achieved thanks to the here followed synergic experimental-numerical approach.

1. Introduction

Various measures are currently being proposed by internal combustion engines manufactures and researchers to improve the performance and, above all, increase the energy efficiency of existing technologies [1]. Between these, gasoline direct injection

* Corresponding author.
E-mail address: m.costa@im.cnr.it (M. Costa).

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(GDI) is surely the one most impacting the automotive market trend of recent years [2]. Compared to port fuel injection (PFI) engines, GDI ones provide higher fuel economy, especially in conjunction with downsizing and turbocharging [3,4]. This last is suitable of being fully exploited in the absence of knocking under the direct injection of gasoline within the combustion chamber, as the mixture temperature is lowered by the subtraction of the fuel latent heat of vaporization from the nearby air that mitigates the tendency to undesired self-ignitions [5].

The liquid spray characteristics and the quality of the air/fuel mixture strongly affect GDI engines power output and pollutants formation [6]. It is long known that it is essential to ensure that all of the injected fuel has maximum contact with the available air to evaporate and then completely burn [7], and various studies have been recently carried out on this subject for optimization purposes [8–12]. The flexible control of the in-cylinder air-to-fuel ratio typical of GDI engines indeed gives the possibility to realize, depending on the time of injection, early or late, and the amount of injected gasoline, either homogeneous (stoichiometric or rich) mixtures or stratified charges [13,14]. These last, in principle, are characterized, at the time of ignition, by a rich zone around the spark plug and leaner zones towards the walls, for overall lean engine operation and lower heat losses at the liner. Present feeling of the automotive community about charge stratification is however still controversial, especially due to the technological difficulties encountered in guaranteeing, at spark timing, the desired equivalent ratio distribution over the whole range of possible application. As a further drawback one must consider emission problems such as excessive light load unburned hydrocarbons and soot formation. These aspects are recognised as both related to local enrichments of the charge deriving form an ineffective mixing of gasoline with air within the combustion chamber and to possible impingement of the spray against the piston or the cylinder walls [15]. Spray impingement is often unavoidable or even intentional [16]: in engine configurations based on the so-called wall-guided mechanism for mixture formation, the piston exhibits a properly shaped nose adjacent to a cavity placed as opposite to the injector, which has just the scope of redirecting the impinging spray droplets and vapor cloud towards the spark plug. Controlling the amount of impacting droplets, their trajectory and the evaporated gasoline mass is a challenging task that strongly suffers the effects of the interaction between the spray and the surrounding air flow [17]. Conversely, in the spray-guided mixture formation mode, the spray and spark are mounted close to each other, and wall impingement is not intentionally pursued to enhance droplet break-up as injection pressure and spray interaction with the surrounding air alone are sufficient to achieve the task. Nevertheless, also in these situations liquid droplets may hit over walls and accumulate as wallfilm [18].

Wallfilm formation is today an important argument in the development of modern GDI engines [19,20]. The dynamics of droplets compounding a spray results from the interaction between shear forces and surface tension. The choice of the injection time must account for the piston position, since the impact of droplets on its hot head not only may cause splashing or rebounding, but also sticking and liquid fuel deposition. The heat transfer from the wall to droplets or the wallfilm determines the so-called secondary evaporation, that is strongly affected by the pressure, temperature and velocity of the surrounding gas (until local vapor saturation), as well as by the value of wall temperature [21–23]. At relatively high surface temperatures, the liquid-solid contact time is brief because the liquid is separated from the surface due to an insulating vapor layer (film boiling regime). The lower limit of temperature for this regime is the Leidenfrost point, below which droplets partially enter into contact with the wall and the heat transfer rate becomes inversely proportional to the surface temperature (transition boiling regime). This occurs until the critical heat flux (CHF) point is reached. As the surface temperature further decreases, droplets make efficient contact with the surface and the heat transfer reaches the highest rates (nucleate boiling regime), till the so-called bubble incipient point. Below this limit, boiling is a consequence of single phase convection [24].

Multiple droplet impact, liquid deposition, secondary atomization and heat transfer, therefore, must be considered in conjunction with injection timing for characterizing mixture formation and combustion development, hence to determine the pollutants amount at the exhaust of GDI engines. Injection time, during the intake phase or during compression, corresponds to different environmental conditions, which necessarily affect possible wallfilm accumulation, also because, obviously, different positions of the piston with respect to the injector determine different conditions of impingement. In the spray-guided combustion configuration the range of injection timing is recognised being narrow for stable overall lean combustion limited by misfire [25]. In engines adopting wall-guided systems, due to the complexity of the liquid and gaseous fluid dynamics, further insight is needed to define the optimized injection timing for low fuel consumption and reduced cyclic variability within the flammable injection timing window. Bonatesta et al. [17] well clarify that the process of fuel vaporization and gas-phase mixing remains essentially incomplete under this mixture formation mode even when early fuel injections are used to enable homogeneous combustion. They identify part load as a matter of concern as a result of spray impingement especially in the higher load-lower speed range, mid load-mid speed range (where high nucleation rates induce copious increases of engine-out soot mass), and in the upper part-load range where high levels of soot concentration (up to 10 million particles per cm^3) are emitted with very small size (23–40 nm).

In this complex scenario, great benefits may derive from a synergic application of detailed methods of analysis, as optical diagnostics and computational fluid dynamics (CFD) [26–28]. CFD models of GDI engines may help in developing control strategies for the highest power output and the lowest environmental impact [29], but surely need a careful validation to be possibly performed not just on the ground of "global" data, as the measured in-cylinder pressure cycle, but also by comparison with detailed information about the spray dynamics or the combustion evolution one may derive if optical accesses to the combustion chamber are available. On the other hand, optical diagnostics may profit of numerical calculations to fill unavoidable gaps in space or time of measurements, or deriving from average over the optical path.

Present work reports the main results of a comprehensive experimental and numerical study concerning the mixture formation and combustion processes in a turbo-charged high performance GDI engine, and is aimed at just showing how the two techniques can be used to fulfill the intrinsic lacks each of each other. The considered engine is modified to allow optical accesses within the combustion chamber with respect to its commercial configuration. A three-dimensional (3D) engine model is developed that includes a properly validated sub-model for the spray dynamics and its impact over walls. Although the optical accessibility permits just a rough view of the in-cylinder spray evolution and impact on the piston head, it gives a valuable term of comparison for the results of the CFD engine model under actual operation.

The realized study has the main objective of highlighting the main features and shortcomings of injection strategies for either stoichiometric or overall lean charge operation. The highly transient nature of the spray interaction with the surrounding air flow, its impingement against the combustion chamber hot walls and the way these affect the liquid fuel evaporation rate are deeply analyzed through the combined experimental-numerical