OPTIMAL CONTROL STRATEGIES FOR LOW FUEL CONSUMPTION IN A GDI ENGINE UNDER SINGLE AND MULTIPLE INJECTION

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ABSTRACT

The optimization of the mixture formation process in a GDI (gasoline direct injection) engine equipped with a high-pressure seven-hole injector is pursued by coupling a 3D model of the in-cylinder processes with an optimization tool. The 3D model of the in-cylinder processes is developed on the ground of experimental data. Injection strategies, as preliminary experimentally characterized on a Bosch tube, are considered as occurring or in a single event or in multiple events. The advantages of splitting injection into four parts are discussed. Optimal injection strategies and time of spark advance are chosen in order to reduce the gasoline consumption, hence to increase the engine energy efficiency. The effects of the mixture formation process on the formation of the main pollutants are also discussed.

Keywords: multidimensional engine modeling, gasoline direct injection, optimization, multiple injections

1. INTRODUCTION

The preferred route towards the reduction of both the fuel consumption and the exhaust noxious emissions in internal combustion engines remains the control of the mixture formation and combustion processes taking place within the combustion chamber, a complicated task, affected by many variables. In the recent years, the high cost and time needed to achieve optimisation through engine bench testing alone has drawn interest of developers towards the use of Computational Fluid Dynamics (CFD) analyses. Nowadays, the link between the need to reduce greenhouse gas emissions and the use of advanced engine simulation is so well assessed, that also the coupling between traditional 3D engine simulation tools with algorithms able to explore the model constants space in an automatic way, as genetic or robust search methods, is being considered. During each iteration, the decision variables are manipulated using various operators (selection, combination, crossover or mutation) to create new design populations, i.e. new sets of decision variables. Optimization algorithms, on the other hand, may be used to drive the choice of a design solution, or configuration, between various alternatives, hence in a role that is more congenial and traditional [Thévenin and Janiga, 2008]. Examples of application of genetic algorithms to the design of diesel engines are found in the paper by Wickman *et al.* [Wickman, Senecal, Reitz, 2001] and de Risi *et al.* [De Risi, Donateo, Laforgia, 2003.]. A more recent application by Dempsey and Reitz [Dempsey, Reitz, 2011] explores the possibility of reducing the pollutant emissions in a reactivity controlled engine, fed with both diesel and gasoline.

Present work is aimed at discussing the assessment of a procedure for the fuel consumption reduction of a GDI engine, based on the optimal synchronization of the injection event within the working cycle.

GDI is nowadays one of the most pursued solutions to improve the performances of spark ignition (SI) engines from both an energetic and an environmental point of view. This is mainly due to the possibility to precisely control and adapt the fuel amount and injection timing to the specific load and speed operating condition. Achievement of optimal charge conditions over the whole working map is affected by many parameters, whose effects are complex and overlapped. This is the reason why injection modulation and splitting are being considered also in SI engines, in analogy with compression ignition ones.

Multiple injection strategies are already employed in present GDI engines under special operating regimes, as for mixture formation at engine cold start, to increase the temperature for the converter light-off, to achieve a smooth idle and to reduce the engine tendency to knock [Kuwahara, Ueda, Ando, 1998]. In the future, these strategies may be used also to control the combustion process and/or to prevent misfiring or high emission levels.

The interactions of multiple injection events between themselves and with the surrounding air motion surely needs further investigation. The synchronization of each single injection event within the working cycle, in fact, must be optimized having in mind a certain objective of power output or pollutants emissions, and accounting for the complex mutual effects of the spray liquid droplets motion and the surrounding air flow. Especially when injection is realised during the intake stroke, the air flow assumes a configuration that strongly depends on the instantaneous valve position and on the pressure difference between the intake ducts and the cylinder. Macroscopic vortexes form under the intake valves having a diameter comparable with the valve diameter. The position of the vortex axes is not fixed but moves as they get open or closed. This determines effects on the spray entering the combustion chamber of an entity that depends on the particular instant of time being considered for injection.

The effects of single or multiple injection strategies on the performance of a single cylinder 4-valve, 4-stroke GDI engine are here numerically analyzed. A 3D engine model, developed by Montanaro *et al.* [Montanaro, Sorge, Catapano, Vaglieco, 2012], is employed to the scope. The runs of the 3D model are driven by the Simplex algorithm to search for the injection strategy and spark advance that reveal optimal for the combustion development. After the optimal injection pressure is identified, the gasoline supply is considered as subdivided into four successive events, each delivering a same mass of gasoline. The optimization algorithm is again used to automatically manage the 3D engine model under multiple injections, hence, it is used to explore the actual advantages of modulating the mixture formation for low consumption and reduced pollutants.

2. THE 3D ENGINE MODEL

The 3D engine model employed within the present study is developed in the context of the software AVL Fire^{TM}. Details of the model assessment are given in the paper by Montanaro *et al.* [Montanaro, Sorge, Catapano, Vaglieco, 2012], where specifications of the engine under study and of the considered seven-hole injector are also given. The approach followed for the simulation of the spray dynamics within the engine cylinder is the classical coupling between the Eulerian description of the gaseous phase and the Lagrangian description of the liquid phase. The train of droplets entering the computational domain in correspondence of the injector holes exit section suffers various concurring effects as it travels, as break-up, evaporation, coalescence. The droplets break-up phenomenon is simulated according to the sub-model of Huh-Gosman, whose constant determining the break-up time, C_1, is to be properly adjusted. The initial size of droplets at the nozzle exit section, is considered as not constant, but variable according to a probabilistic log-normal distribution, whose variance, σ, is another parameter to be properly tuned. A preliminary experimental characterization of the employed seven-hole injector, here not described for the sake of brevity, served to the spray sub-model validation, hence to the C_1 and σ definition, according to an automatic procedure assessed by Costa *et al.* [Costa, Sorge, Allocca, 2012].

3. OPTIMIZATION OF THE INJECTION STRATEGY

As previously said, present work aims at investigating the injection strategy realising the mixture whose characteristics are optimal for power generation in a high performance GDI engine. Two analyses are effected, one for single injection, by changing injection pressure (p_{inj}) and start of injection (SOI), one for injection split into four equal parts, by changing the start of the first injection event (SOI_1) and the dwell time between each event and the next. The dwell time is assumed constant between the first and the second, the second and the third, the third and the fourth injection event. In all the situations, the Simplex algorithm is used to search for the inputs maximizing the indicated mean effective pressure (IMEP) in the closed valve period of the engine working cycle. The injected gasoline mass is considered constant, namely equal to 20.16 mg/cycle, in order to realize a lean stratified combustion (air to fuel ratio, A/F, equal to 16.9) at the engine speed of 1500 rpm. Another design variable of the optimization problem is identified in the time of spark ignition (start of spark - SOS), since it obviously strongly affects the combustion development.

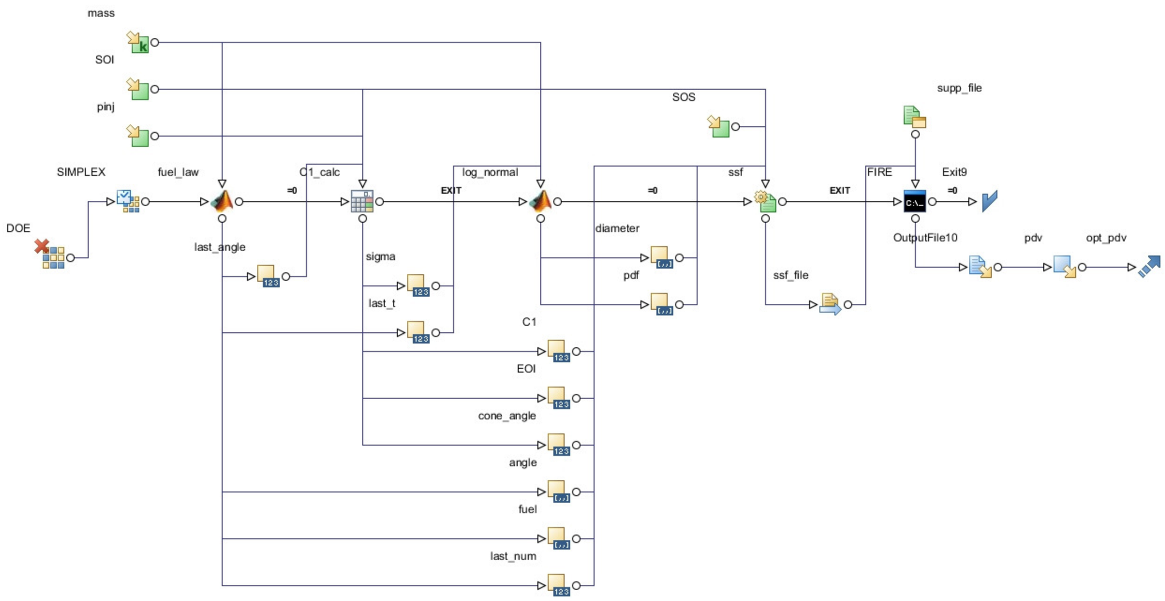

Figure 1: Flow chart of the optimization problem for the single injection case.

The choice of the range of variation of the samples, as well as the step between successive samples, that obviously influences the efficiency and speed of the optimization procedure, is properly made starting from a certain initial point.

3.1. Optimization in the single injection case

The scheme of the optimization problem solved in the case of single injection is reported in Figure 1. The input variables defining the injection strategy and the SOS are visible. The definition of the injection strategy, accounting for an injection pressure variation in the range 5 to 15 MPa, needs a discussion.

The injector under study, as previously said, was experimentally characterized by injecting gasoline, according to some engine strategies, in an optically accessible vessel for the measure of the single jet cone angle and penetration length. The instantaneous mass flow rate was also measured in a Bosch tube [Bosch, 1966, Wallace, 2002]. Measured cone angles and mass flow rates, indeed, are input variables of the spray sub-model included in the 3D engine model. The experimental availability of these variables, however, is limited to a few values of the injection pressure. Therefore, a scaling is included within the project of Figure 1 in order to account for the variation of this quantity at constant injected mass. Figure 2 shows the mass flow rate measured at the injection pressure of 6 and 10 MPa, together with the profiles relevant to the injection pressures of 5 and 15 MPa, derived by scaling the experimental data on the ground of a coefficient proportional to the square root of the difference between injection and environment pressure. On the other hand, the employed spray sub-model also needs the specification of the initial droplets size, namely the definition of the value of the variance of a log-normal distribution whose expected value is evaluated according to the following formula:

$$D_{th} = C_d \left(\frac{2\pi\tau_f}{\rho_g u_{rel}^2} \right) \lambda^* \quad (1)$$

being τ_f the gasoline surface tension, ρ_g the surrounding gas density, u_{rel} the relative velocity between the fuel and the gas, C_d a constant of the order of the unity (indeed taken equal to the unity), and the parameter λ^* deriving from the hydrodynamic stability analysis and indicating the dimensionless wavelength of the more unstable perturbation to the liquid-gas interface at the injector exit section. Therefore, an interpolation of the optimal values of the C_1 and σ constants found according to the procedure defined in [Costa, Sorge, Allocca, 2012] is used, as shown in Figure 3. With interpolated data, all the needed distributions of initial droplets size can be defined. As an example, Figure 4 represents four distributions for different injection pressures. The reliability and portability of the spray sub-model as this variable is changed, indeed, was proven by authors also with reference to other injectors.

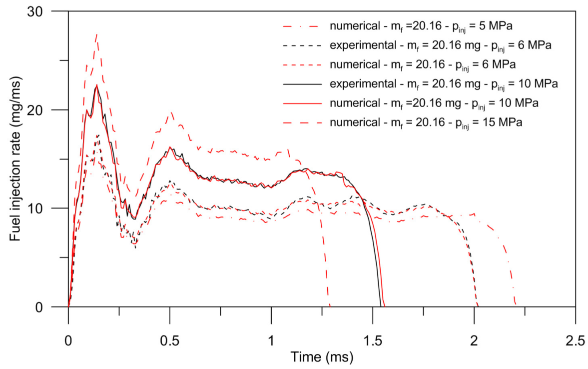

Figure 2: Mass flow rates: measurements and numerical scaling, at 6 and 10 MPa.

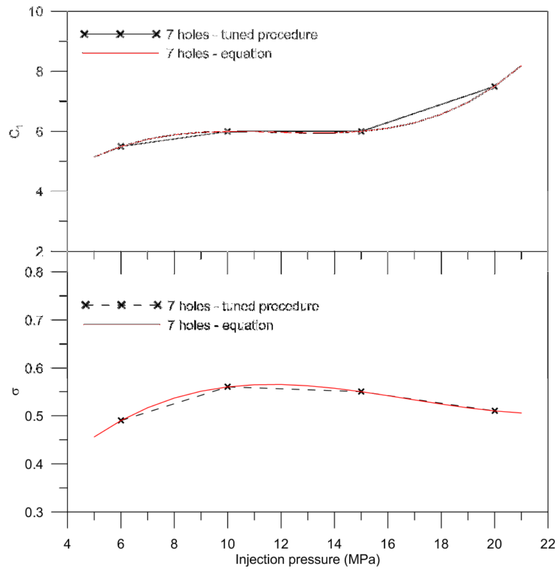

Figure 3: Interpolation of the optimal values of the constant C_1 (top) and the variance (bottom).

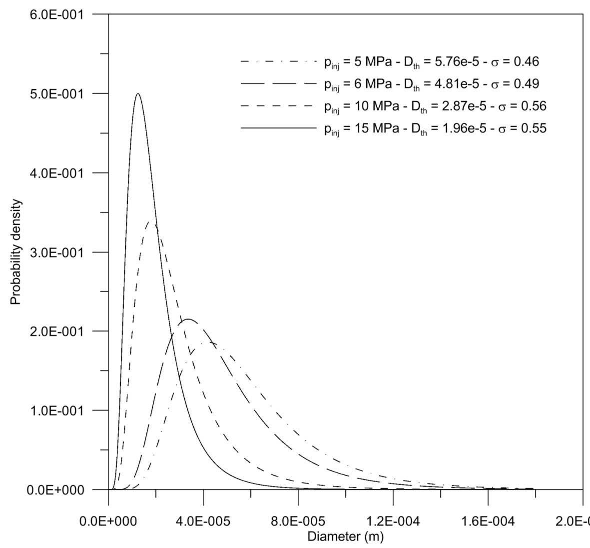

Figure 4: Initial size of droplets at p_{inj}= 5, 6, 10, 15 MPa.

Results of the optimization analysis relevant to the single injection case are reported in Figures 5 and 6, where the IMEP of each computed cycle in the closed valve period, made dimensionless with respect to the value relevant to the starting point cycle ($IMEP_{ref}$), is represented in a bubble plot in the p_{inj}-SOI and the p_{inj}-SOS planes. The triple of values of p_{inj}, SOI and SOS maximizing the engine performance is just the one assumed as reference (staring point), namely p_{inj}=6 MPa, SOI=650° (58° after inlet valves closing, IVC) and SOS=707° (13° before the top dead center, BTDC).

The effect of the injection strategy on the main pollutants is clarified by Figures 7 and 8. Figure 7 is a bubble plot in the p_{inj}-SOI plane, where the bubble size is proportional to the ratio between the NO amount at the exhaust valves opening (EVO) of each computed cycle and the one assumed as reference case (NO_{ref}), also at EVO. Figure 8 is a bubble plot representing the ratio between the unburned equivalence ratio (UER) at EVO (proportional to the unburned hydrocarbons amount) and the one of the reference case.

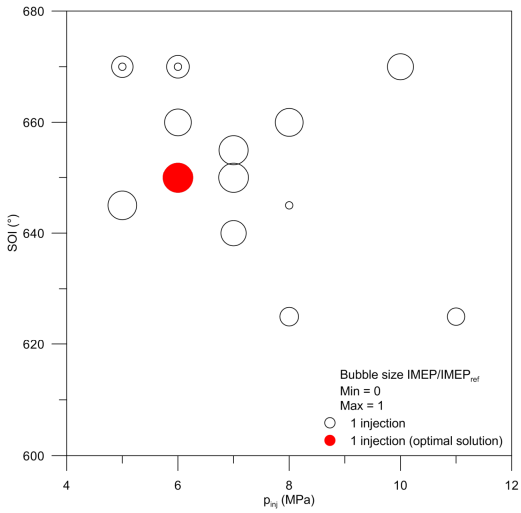

Figure 5: IMEP: bubble plot of the single injection optimization in the p_{inj} - SOI plane.

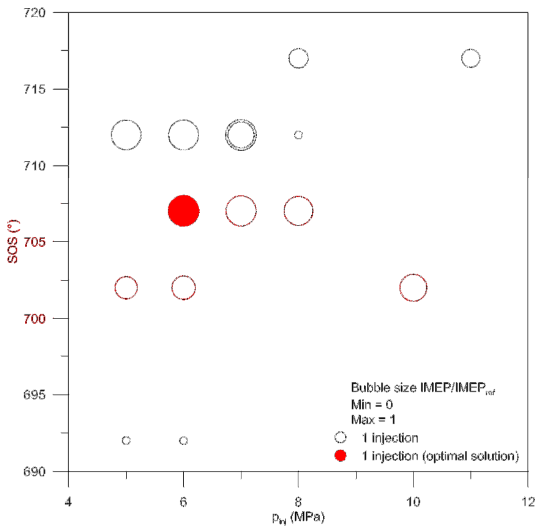

Figure 6: IMEP: bubble plot of the single injection optimization in the p_{inj} - SOS plane.

The optimal solution is characterized by a quite high value of the NO amount at the exhaust, while the unburned hydrocarbons are really low.

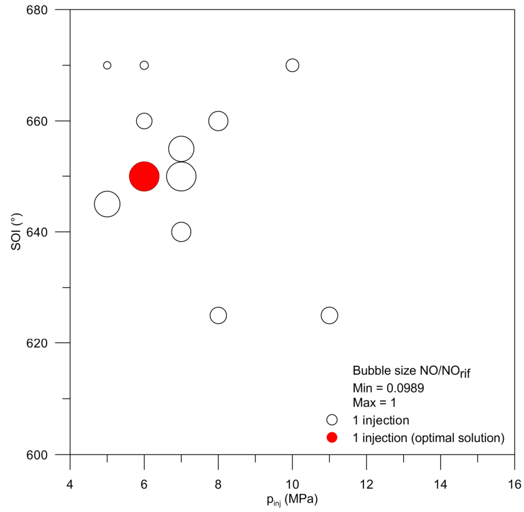

Figure 7: NO: bubble plot of the single injection optimization in the p_{inj} - SOI plane.

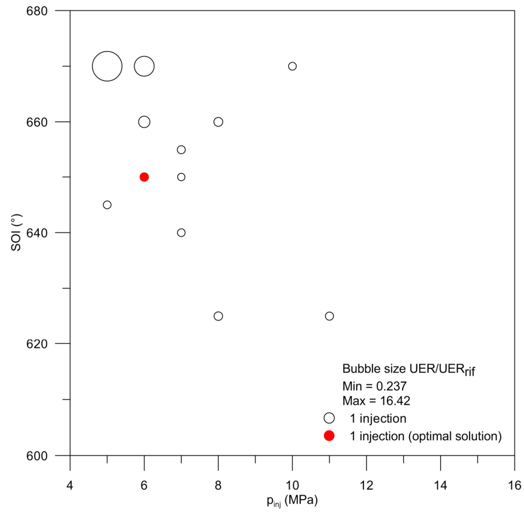

Figure 8: Unburned equivalence ratio: bubble plot of the single injection optimization in the p_{inj} - SOI plane.

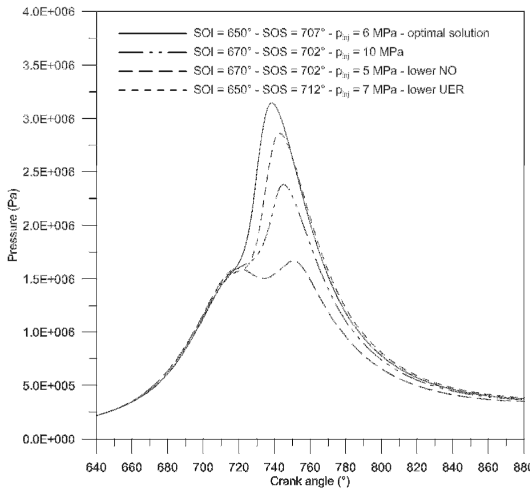

Figure 9: Computed in-cylinder pressure for four different injection strategies.

The dramatic effect of the chosen variables on the in-cylinder pressure at moderate-load is visualized in Figure 9, where four different in-cylinder pressure cycles are plotted. It is evident that the optimal solution has a cycle area greater than the other ones. The cycles relevant to the lower NO case and the lower unburned hydrocarbon case are also reported. These two are really characterized by a low power output, especially the one relevant to the lower NO value.

3.2. Optimization in the multiple injection case

The afore described analysis leads to individuate the optimal injection pressure at 6 MPa. Keeping this variable as fixed, a further analysis is here discussed, where injection is considered as split into four parts. Figure 10 represents the comparison between the single injection case and two different quadruple injections, each characterized by a certain value of the constant dwell time between successive events (kept constant). Each of the four injections is assumed to deliver the same fuel quantity, hence 5.04 mg, for a total of 20.16 mg/cycle.

The optimization analysis is performed by changing the SOI of the first injection event, SOI_1, the dwell time between successive events, and the time of SOS. Figures 11 represents the IMEP of each computed cycle in the closed valve period, made dimensionless with respect to the value relevant to the reference single injection cycle ($IMEP_{ref}$) (same as for single injection) in the SOI_1-SOS plane. The optimal quadruple strategy is characterized by SOI_1=625° (25° before the SOI found as optimal in the single injection case) Dwell= 7°, SOS=692° (28° BTDC). The optimal solution for the quadruple injection case comes out being better than the optimal solution for single injection. As shown in Table 1, that is a summary of the results of the single case and quadruple case optimization processes, a gain equal to the 8.9% in the IMEP is evident for injection split into four parts. Figure 12 and Figure 13 shows, respectively, the bubble plots relevant to the NO and unburned equivalence ratio, always made dimensionless with respect to the relevant quantities of the reference single injection case.

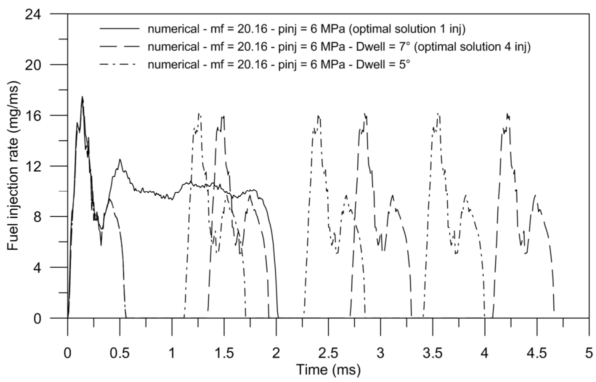

Figure 10: Mass flow rates for single and quadruple injections at 6 MPa at constant total mass.

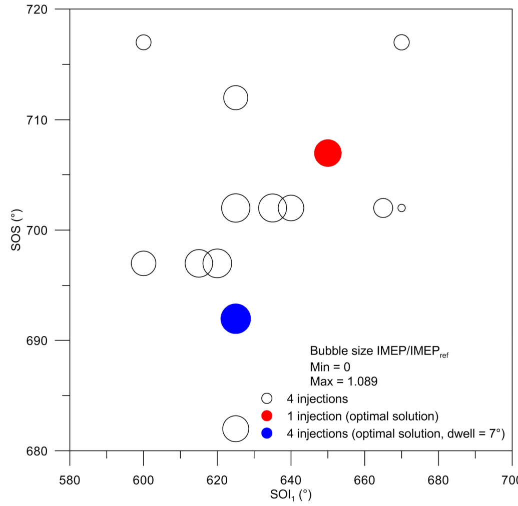

Figure 11: IMEP: bubble plot of the quadruple injection optimization in the SOI_1 – SOS plane.

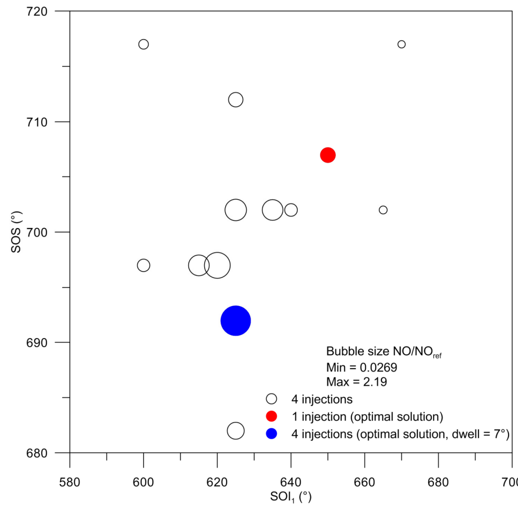

Figure 12: NO: bubble plot of the quadruple injection optimization in the SOI_1 – SOS plane.

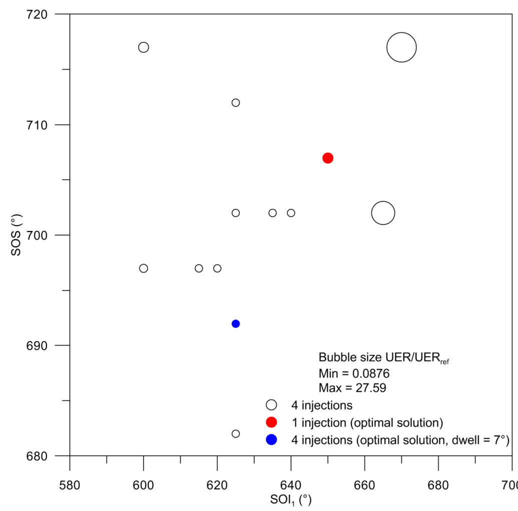

Figure 13: Unburned equivalence ratio: bubble plot of the quadruple injection optimization in the SOI_1 – SOS plane.

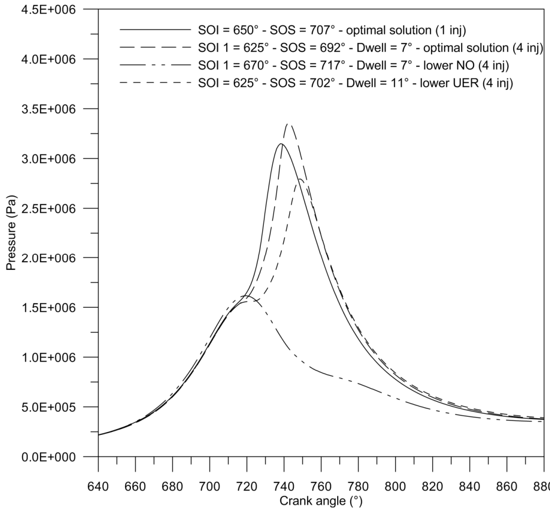

Figure 14: Computed in-cylinder pressure for optimal single and optimal quadruple injections. Lower NO and UER cases for quadruple injection are also represented.

Optimal	$IMEP/IMEP_{ref}$	NO/NO_{ref}	UER/UER_{ref}
1 injection	1	1	1
4 injections	1.089	2.19	0.0977

Table I. Summary of the optimization results

The NO amount, indeed, suffers a bad effect from the injection splitting, whereas an improvement in the burning of hydrocarbons is evident. Refer to Table 1 to quantify these aspects.

Figure 14, finally shows the comparison between the pressure cycles relevant to the optimal single and the optimal quadruple injection. The gain in the pressure cycle area, that obviously reflects in a gain of about the 9% in the gasoline consumption in the considered lean mixture case, is well visible. Two other pressure cycles are reported: the one relevant to the lower NO amount for four injection (NO/NO_{ref}=0.0269), and the one relevant to the lower unburned hydrocarbons at the exhaust(UER/UER_{ref}=0.0876), that however is meaningless due to the low power output.

4. CONCLUSIONS

Results of optimization analyses devoted to increase the energy efficiency of a GDI engine under overall lean stratified charge conditions (at moderate speed, moderate load) are discussed.

The study is performed through numerical simulation, by employing a 3D engine model assessed on the ground of experimental data. Under both single and quadruple injections, the 3D engine model is automatically driven by an optimization algorithm that searches for the maximum pressure cycle area (in the pressure volume plane), at constant injected mass of gasoline.

Under single injections the value of injection pressure is varied between 5 and 15 MPa, while the start of injection is changed in the range 600°-670° (intake valves close at 592°, TDC is at 720°). A third variable is considered, namely the time of spark advance, changed in the 682°-717° range. The value of injection pressure found as optimal is p_{inj}=6MPa, the SOI=650° (injection all realized during compression), SOS=707°. The point found as optimal, with respect to the others, is also characterized by a low value of unburned hydrocarbons at the exhaust, but a quite high value of NO. However, this may be considered as a secondary problem due to the possibility to resort to after-treatment systems of this kind of pollutant.

The optimization analysis relevant to the four injection case leads to the interesting result of a further gain in the energy efficiency achievable through splitting injection. This can be quantified as equal to about the 9%, with a positive effect also on the unburned hydrocarbons.

The procedure developed by authors for the optimization of the engine performance has a broad range of applicability. It is here considered to increase the energy efficiency of a lean stratified combustions in a high performance GDI engine.

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