Injection Strategy for GCI Engine at Low Load

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Abstract Gasoline Compression Ignition (GCI) engine showed the potential to match the efficiency of compression ignition (CI) engines with reduced emission of NOx and soot. The objective of this work is to understand the influence on gasoline combustion of different injector parameters such as umbrella angle, number of injection and injection timing when a 95 RON gasoline is direct injected in a commercial Diesel engine. Experiments were performed in a single-cylinder Diesel engine fueled with direct-injected 95 RON gasoline at a constant fueling rate leading to a global fuel-air equivalence ratio of 0.3. Engine speed was set to 1500 rpm. Intake pressure was set to 1 bar in order to investigate typical low load operating conditions in which turbocharger can not supply extra pressure. Intake air was heated up in order to enable the autoignition of gasoline. Three different injectors with 156°, 120° and 90° umbrella angle were tested. For each injector, experiments were carried out with a single and a double injection strategy and over a wide range of injection timings. The behavior of the three injectors was compared in terms of engine performances and pollutant emission. Advanced injection timings were necessary to enable gasoline autoignition. Results showed that a wide umbrella angle can limit the advance in injection timing because of part of the fuel is directed towards the squish region and do not participate at the combustion event. A narrower injection angle allowed to better concentrate the fuel inside the piston head bowl: the autoignition of gasoline originated from fuel-air mixture characterized by richer distribution of the local equivalence-ratio, improving combustion efficiency and reducing the formation of HC and CO while maintaining low emission of NOx. Moreover, results from experiments showed that because of spray-bowl geometrical interaction, abnormal NOx emission could be obtained in correspondence of certain early injection timings. Under these conditions, part of the exhaust NOx can be trapped in the hot residuals, reacting with gasoline fuel injected in the subsequent cycle leading to abnormal advance in combustion phasing. For both injectors, a double injection strategy was employed to introduce the sufficient fuel stratification necessary to reduce the heat release rate and the combustion noise. For low load operation of GCI engine and for a fixed bowl geometry the two injectors with 156° and 120° offered better performance in terms of indicated efficiency while maintaining acceptable level of noise. On the other side, a 90° injector showed the lower emission of NOx and HC.

Keywords: GDCI, Injection Strategy, Low Load, GPPC, Low CO2

1. Introduction

Gasoline Direct-Injection Compression Ignition (GDCI) engine showed potential to increase the efficiency of gasoline engine while maintain low NOx and Soot emission [1]. In GDCI engine, high octane fuel is directly injected into the cylinder of a Compression Ignition (CI) engine and autoignites because of the compression work of the piston. The high Compression Ratio (CR) enables efficient combustion while the strong resistance to the autoignition of gasoline fuels enables Partially Premixed Combustion (PPC), lengthening the fuel-air mixing period and avoiding that local equivalence ration and flame temperatures responsible for NOx and Soot production [2]. Gasoline PPC has been shown to be effective at high load operating conditions [3]–[5], however low load operations still present some challenges due to the reduced propensity of fuel to autoignite [6], such as high HC and CO emissions and difficulties to control the combustion phasing. Great effort have been done in order to investigate on possible solution to improve fuel autoignition propensity at low load. In [7]–[9], a Variable Valve Train (VVT) was employed to enable rebreathing of exhaust gases to promote gasoline autoignition by trapping hot residual in the cylinder. In [1]A Variable Geometry Turbocharger specifically developed in [10] to operate at low load in GCDI engines was also employed in [8], [11] in order to supply increased pressure at the intake as a mean to improve fuel reactivity and combustion stability. Other studies from Foucher et al. [12], [13] investigated the potential of seeding the intake of the engine with chemical species such as ozone to improve the autoignition propensity of gasoline fuels via modification of the combustion reaction path. Accordingly to the technical solution employed to extend the GDCI range toward lower load, the injection system and the injection strategy have to be adapted in order to promote the autoignition propensity of the fuel. Autoignition enhancement based on fuel reformation [9], [14] or combustion promotion by chemical species [13] generally need the injection event to be placed early during compression stroke, while if rebreathing of exhaust gases is employed to increase the thermal charge of the intake air, injection can be placed closer to TDC . Moreover, in [7], [11], [15] the authors showed the importance of the injection strategy to induce the necessary fuel stratification required to obtain lean and efficient combustion while avoiding excessive heat release rate and combustion noise. Moreover, also technical parameters such the umbrella angle may influence the fuel distribution inside the combustion chamber. The influence of the umbrella angle in CI engine was deeply investigated for Diesel engine, and generally wide spray trajectory was demonstrated to be beneficial for Diesel combustion because of the improvement in NOx Soot trade off [16]. However, other authors have demonstrate that narrower umbrella angle can be beneficial when CI engine are fueled with Gasoline. In fact, narrower umbrella angle showed potential to help to concentrate the fuel charge inside the cylinder bowl obtaining more reactive and stable autoignition of gasoline [7], [17] because of a more favorable fuel stratification.

The aim of the present work was to evaluate the influence of the injector's umbrella angle on the low load operation of a CI engine fueled with high octane gasoline. Experiments were performed for single and double injection strategy while three injector with respectively 90, 120 and 156° umbrella angle were employed to inject the fuel over a wide range of injection timings. Results from the experiments and spray calculation were employed to understand the impact of the umbrella angle and injection timing on gasoline combustion and pollutant emissions.

2. Experimental setup

2.1 Engine Setup

Experiments were carried out in a Peugeot DW10-series Diesel engine converted for single-cylinder operation. An electric engine was employed to maintain a constant rotation speed of 1500 rpm during all the experiments. The piston geometry showed in Fig. 1 gives a compression ratio (CR) of 16. Other engine characteristics are listed in Table 1. To attain GCI the engine was fueled with commercial 95 RON gasoline. A high pressure pump, connected to a Diesel common rail system, supplied a 400 bar injection pressure. In order to investigate the impact of the umbrella angle, three different Delphi Diesel injectors, with a wide (156°) middle (120°) and a narrow (90°) umbrella angle, (hereinafter UA156, UA120 and UA190, respectively), were employed. All injectors have 8 holes with 131μm in diameter. A constant fueling rate of 7.8 mg/cycle corresponded to a global fuel-air equivalence ratio of 0.3. Intake pressure was kept constant at 1 bar in order to simulate low load operation in which turbocharger are not able to supply extra pressure at the intake. Substituting more complex VVT systems by electrical heaters, allowed the authors to control the thermal content of the intake charge while avoiding the influence of the air management system, and to focus the attention on the impact of the injection system. Thus, the intake temperature was set to 205°C and maintained constant for all the experiments. Brooks 5800 series mass flow controllers were employed to control each fluid flow, dry air was supplied by a compressor and the intake air temperature was managed by electrical heaters. Pollutant emissions at the exhaust were measured by a Horiba 7100 gas analyzer. The author would like to clarify that all the experiments were conducted with the same piston bowl geometry. Consequently, this work has not to be intended as an optimization process. In fact, GDCI combustion are expected to be sensitive to the combustion chamber shape, compression ratio and air management system.

Bore	85 mm
Stroke	88 mm
Rod length	145 mm
Displaced volume	499 cc
Geometric compression	16:1

Table 1. Engine characteristics

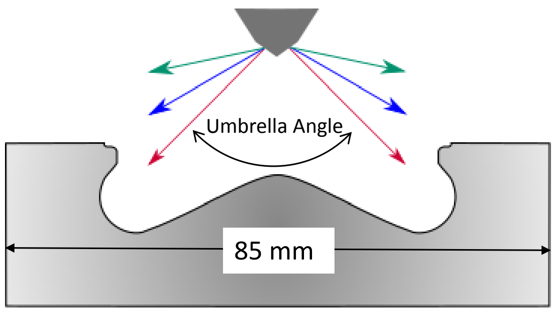

Figure 1.Piston head bowl and spray trajectories for 90° (red), 120° (blue), 156° (green) umbrella angles.

Thus it is important to realize that the results from experiment are not all-encompassing and that an optimization process should optimize the combustion chamber geometry for each injector type. The goal of this study was to provide a perspective of the impact of the umbrella angle over the GDCI engine combustion at low load when a particular injector is employed to match other technological requirements.

2.2 Spray Target Position Determination

A computation model was developed and employed to determine the spray target position as a function of the injection timings and the included angle of the injector employed. The model calculates the engine kinematics and the piston head location as a function of the crankshaft angular position. Then, considering the experimental in-cylinder thermodynamic conditions at the start of the injection, the spray axis penetration is calculated based on correlation developed in [18] for Diesel sprays. The previous mentioned correlation was developed and validated for a large set of experiments reproducing Diesel engine conditions in a constant volume vessel in which the spray has was free to penetrate for about 60 mm. Based on previous experiments by the authors, the fuel spray penetration is affected by the fuel nature because of the different physical properties. However, the difference in the spray axis penetration of diesel and gasoline fuel is negligible if the injection event is concluded before the onset of the combustion and for the range of distances available to the spray to penetrate inside the combustion chamber of a light duty engine.

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3. Results and Discussion

3.1 Single Injection

In order to understand the impact of the Umbrella Angle (UA) on a Gasoline Compression Ignition (GCI) engine, the three different injectors were tested for a constant fueling rate while the Start of Injection (SOI) was moved from Top Dead Center (TDC) toward earlier injections timings and for a constant intake temperature and pressure. Figure 2 shows the combustion efficiency trends as a function of SOI. The combustion efficiency shows drops which are indicating the boundaries of the admitted SOI range for each injector. The SOI range boundary closest to TDC seems to be independent from the injector UA. For all the injectors, gasoline should be injected about 20 CAD before TDC in order to avoid misfire and let the fuel to autoignite with a stable combustion efficiency. For a fixed Compression Ratio (CR), this limit is likely to be related with the autoignition propensity of the fuel (i.e. octane number) and with the thermodynamic conditions of the air at the intake. On the other side, the earlier boundary of the SOI range is strongly affected by the UA. In Figure 2 (a), the early SOI limit could be identified by drops in combustion efficiency caused by the increased amount of fuel that was directed towards the squish region and that did not participate to the combustion event. It should be noted that, while the UA90 and UA120 injectors enabled the autoignition of the gasoline with a combustion efficiency higher than 98% over a SOI range of 35 CAD and 20 CAD

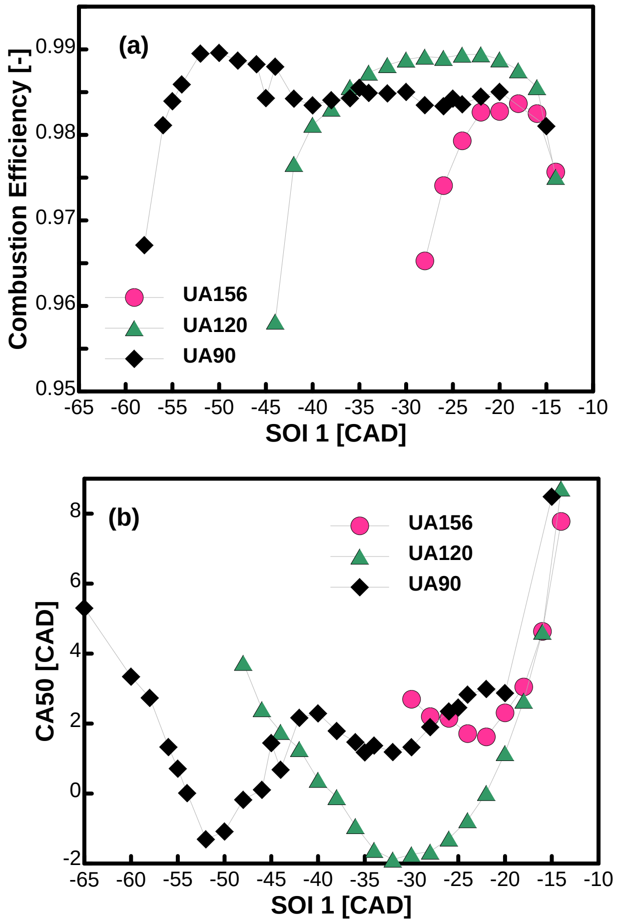

Figure 2 Combustion Efficiency and Combustion Phasing as a function of the Injection Timing for different umbrella angles

respectively, in the UA156 case the two boundaries of the SOI range tended to collapse. Because of the wide trajectory imposed to the spray, the UA156 injector did not allow the spray to target the bowl far enough from TDC to give at the fuel necessary time for autoignition. Inside the SOI range determined by the Umbrella Angle, the combustion behavior and the formation of pollutant is strongly dependent on the injection timing. However, observing the results from the experiments reported in Figure 2, Figure 3 and Figure 4, it could be noted that even if different injectors offer different performances, recurrent paths can be found for the combustion related parameters when the injection timing is moved between the SOI range boundaries. Figure 4 shows for each injector employed, the spray trajectory and the spray target position as a function of SOI. The piston bowl section has been divided in four regions, according to the different combustion behavior observed during the experiments. For each injector, when spray is directed towards the upper bowl, part of the fuel could

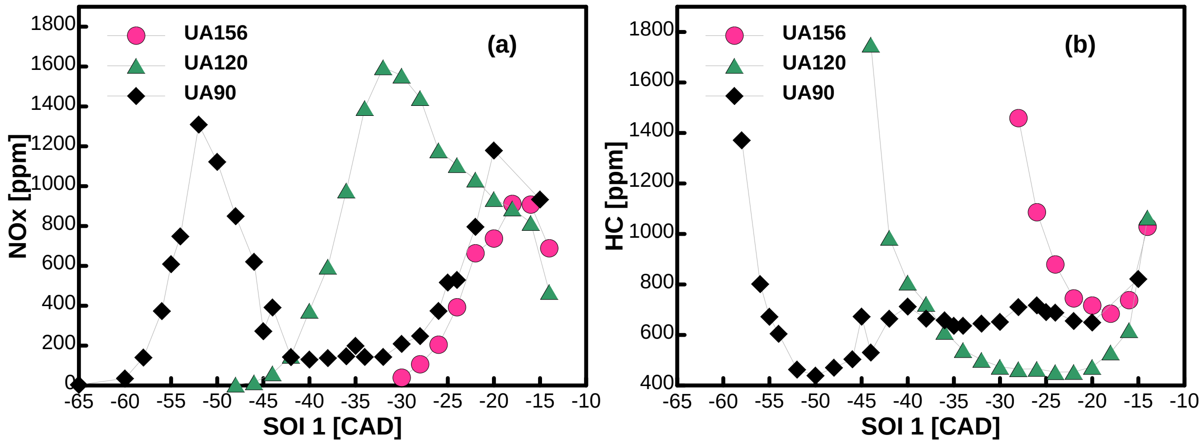

Figure 3 NOx emission and HC emissions as a function of the Injection Timing for different umbrella angles.

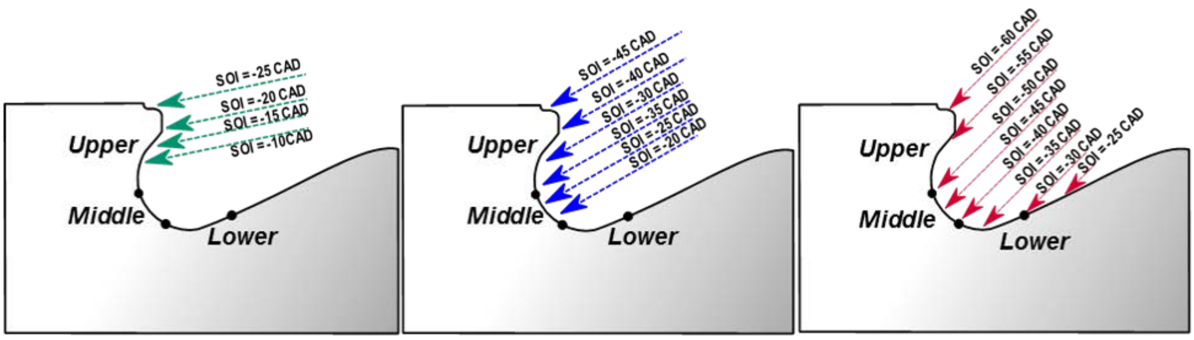

Figure 4: Spray target position as a function of SOI for the UA156, UA120 and UA90 injectors.

get in the squish region leading to increased HC formation, as shown in Figure 3(b) and low combustion efficiency, as reported in Figure 2 (a). Figure 3 (b) and Figure 3(a) show that if SOI was moved toward TDC when spray targets this region,

less HC originated from the squish region and the NOx emission increased as a consequence of the higher combustion temperature induced by the increase of local fuel to air equivalence ratio (ϕ) and because of the advance in the combustion phasing showed in Figure 2 (b). Increasingly moving the SOI closer to TDC, allowed to inject the fuel when the piston head is closer to the injector nozzle, so that the spray could target the middle portion of the piston head bowl, confining the fuel air mixture preparation inside the bowl. In this region, the combustion efficiency reached a maximum of about 98,5% for the UA90 and UA120 injectors. Likewise, HC from squish region are avoided. For the UA156 injector, however, the misfire limit came before the spray could hit the middle portion of the bowl. Figure 3(a) shows that this region was characterized by a peak in NOx production for all the injector tested. However, nitrogen oxide emission progressively reduced when SOI is systematically moved toward TDC because of the progressive delay in combustion phasing showed in

Figure 2 (b). Systematically moving the SOI closer to TDC conduced the spray target position to move toward the lower part of the piston bowl, as reported in Figure 4. However, the UA120 injector needed a SOI of -20 CAD to direct the spray in this regions, so

that misfire limit take place at the same time. The narrow spray trajectory imposed by the UA90 allowed to send the fuel spray toward the lower portion of the bowl when the injection event toke place at least 35 CAD before TDC. In this region, the NOx and HC emission are less influenced by the SOI and also the CA50 showed reduced sensitivity to the injection timing. This was probably due to the fact that the spray head hit the bowl flow with a constant angle and so the ϕ distribution inside the piston head bowl is less influenced by variation in the injection timing and spray target position. If fuel is injected lately during compression stroke with 90° umbrella angle injector, the spray impacts the bowl pip. In this region, an increase in NOx emission was observed while CA50 was retarded by the SOI, which is somewhat counterintuitive. However, results from simulation in [15] showed that NOx production can be stimulated by the high combustion temperature originated by the reach fuel pocket autoigniting when high fuel stratification is induced by injection close to TDC. For

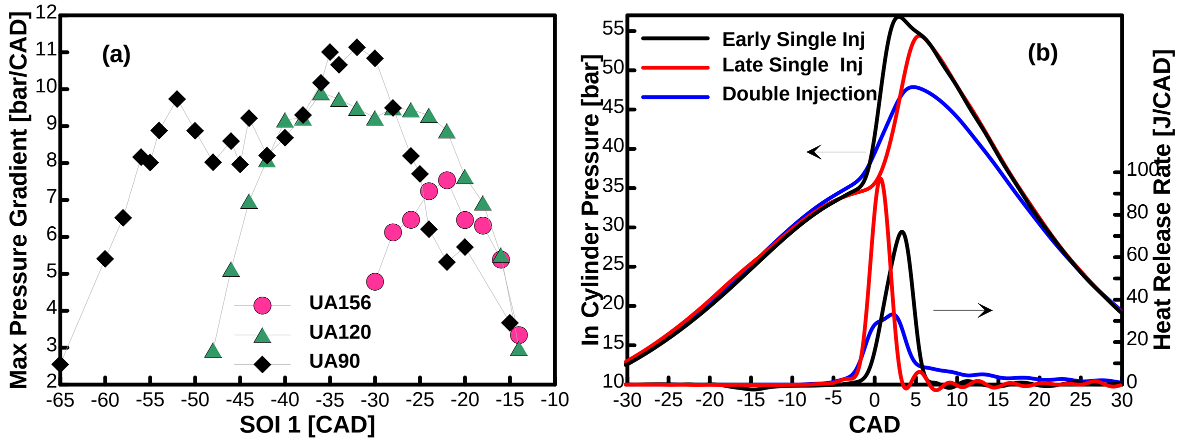

Figure 5: Max Pressure Gradient as a function of SOI (a). In-Cylinder Pressure and Heat Release Traces For Single Injection at SOI=-55CAD (Black Lines), Single Injection at SOI = -26 CAD (Red Lines) and for a Double Injection (Blue Lines).

all the injectors, the in cylinder pressure gradient are showed in Figure 5(a). Over the most part of the SOI range, results showed excessive in cylinder pressure gradient caused by the premixed combustion of gasoline. When higher stratification was induced by delaying the injection timing closer to TDC, the in-cylinder pressure gradient decreased because of the reduction in heat release rate and because of the delay in combustion phasing, as showed in Figure 5 (b).

3.2 Effect of Residual NO on Combustion Phasing

Observing Figure3(a) it can be noticed that when the UA90 injector was employed, a bump in NOx emissions occurred for SOI between -60CAD and -45 CAD. In correspondence of this high NOx emissions, an acceleration in the CA50 can be observed in Figure 2(b). Moreover, more precise analysis of the exhaust gases reported that more than the 80% of NOx measured were composed by NO. In previous work [19], [20], NO and NO2 showed to possess a promoting effect on premixed combustion of iso-octane. So, authors interrogates if in that high NOx formation regime, part of the nitrogen oxide could have been trapped in the residual burnt gases and reacting with gasoline in the subsequent cycle, fuel causing an abnormal advance in the combustion phasing. An alternate-injection operating mode, in contraposition to the typical continued-injection operations was employed to remove the effect of residual NO on gasoline autoignition. Under the alternate-injection mode, fuel was injected only every two cycles. In this way, every combustion cycle was followed by a cycle in which only fresh air flew into the cylinder, enabling the dilution of the residual trapped gas and cleaning up the combustion chamber from residual NO. Figure 6 compares the CA50 for the alternate and the continued injection mode for the same SOI sweep. In order to compensate for the reduced wall temperature induced by alternate combustion cycles, the intake temperature had to be increased of 13°C. The intake temperature increase was evaluated at SOI=-60 CAD, where NOx production was negligible and combustion phasing independent from the effect of trapped NO, by matching the CA50 measured during the continued injections mode.

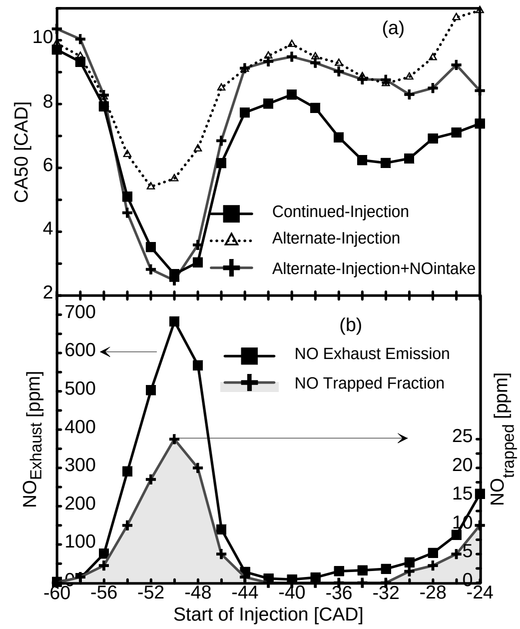

Figure 6 CA50 as a function of SOI for the continued-injection mode, alternate-injection mode and alternate-injection mode with NO addition at the intake (a). Exhaust NO concentration measured in the continued-injection mode and the estimated NO trapped fraction

According to [19], [20], limiting the NO concentration coming from preceding combustion cycle, retarded

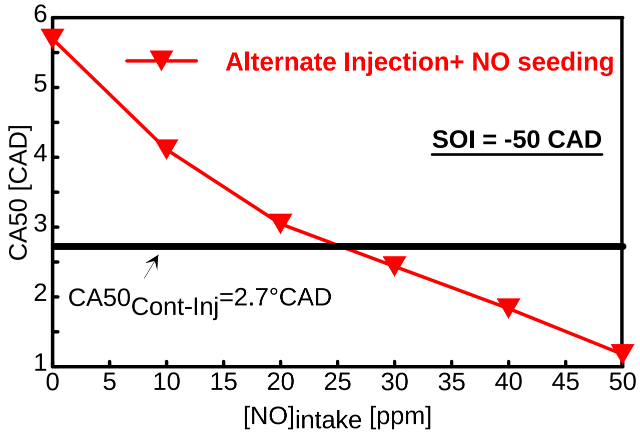

Figure 7 Evaluation of the NO trapped fraction. CA50 as a function of NO concentration, during alternate-fired mode.

the CA50 over the whole range of SOI. Figure6(b), shows the NO concentration)measured at the exhaust in the continued-injection mode. Comparing Figure6(a), and Figure6(b), it could be seen that a maximum offset between the two CA50 traces of ~3 CAD occurred for SOI=-50 CAD, matching with the 682 ppm peak in NO concentration at the exhaust. To estimate the trapped fraction of NO, the engine was ran in alternate-injection mode, and the injection timing set in correspondence to the peak of NO production, at SOI =-50 CAD. Then, pure NO was systematically injected up to when the promoting effect of the nitric oxide was such that to restore the CA50 previously obtained in the continued-injection mode. As shown in Figure 7, 25 ppm of NO were needed to match such CA50. The NO trapped fraction was then estimated at SOI = -50 CAD as the ratio between the 25 ppm NO concentration at the intake and the 682 ppm measured at the exhaust under continued-injection operation. A value of 3,66% was obtained. Because in first approximation, this ratio depends only by the engine internal fluid-dynamic, it could be applied for estimating the NO trapped over the entire SOI range. Therefore, the NO trapped fraction was calculated and used to seed the intake of the engine during the alternate-injection operations over the entire SOI range investigated: results are reported into Figre 6(a). The CA50 trends obtained well fit the continued-injection CA50 over the SOI range involved in high NOx production, i.e., up to for SOI of -46 CAD. It could be deduced that at early injection timings, if piston geometry and injection strategy yield to high NOx formation, a fraction depending on the speed and the engine geometry could remain trapped within residual gases, promoting autoignition. At later SOI, i.e. SOI > -44 CAD , the NO trapped fraction become negligible, and the onset of combustion is mainly regulated by local stratification of temperature and equivalence ratio.

3.3 Double Injection Strategy

Despite the reduced charge injected into the engine, a single injection strategy led to high in-cylinder pressure responsible for excessive noise and mechanical solicitations over the most of the SOI range. Double Injection can be employed to shape the heat release rate and to reduce the in cylinder pressure gradient, like showed in Figure 5(b).The influence of the umbrella angle was then investigate while a double injection strategy was adopted. The injection duration was adjusted in order to obtain an equal repartition of the fuel mass over the two injection events. Both the injection timings for the first and second injection were varied over a wide range of SOI. In order to obtain combustion efficiency higher than 98%, the SOI1 had to be limited at -50 CAD, -40 CAD and -30 CAD for the UA90, UA120 and UA156 injector respectively. On the other side, SOI 2 can be employed to extend the SOI range up to TDC for all the injector tested with combustion efficiency around 99%. Consequently, double injection strategy improve the capacity of the injection system to manage fuel stratification if compared to a single injection strategy, extending the SOI range in which fuel stratification is obtained. As reported by other authors [7], [8], acting on the injection timing of the last injection (SOI2) enabled the control over combustion phasing. As showed in Figure 8(b), for all the injectors tested, the CA50 is a monotonic function of SOI2, for second injection taking place later than 15 CAD before TDC. This results indicates that for earlier SOI2, because of the too advanced SOI of the two injection events, the combustion generates from too much premixed charge, which autoignition propensity is mainly driven by chemical kinetics. Consequently, for advanced double injection, combustion approaches homogenous charge compression ignition (HCCI) combustion in which fuel simultaneously autoignites inside the whole combustion chamber volume leading to high pressure gradient, as shown in Figure 8(c). Noise level could be reduced with the double injection strategy, which enabled smoother heat release rate for a constant CA50, if compared to single injection strategy, as showed in Figure (5b). The lowest noise level were obtained for SOI2 later than 15 CAD before TDC. In-cylinder pressure gradient only slightly depended on the combustion phasing in this region, and the most influencing factor revealed to be the separation between the two injection events. Consequently, for a fixed SOI2, combustion noise could be controlled via the timing of the first injection. The noise performance of the three injectors is likely to be related with the local distribution of the equivalence ratio which impact on the development of the heat release. As shown in Figure 8 (d), the lower combustion noise observed in the UA90 case are in accordance with the lower

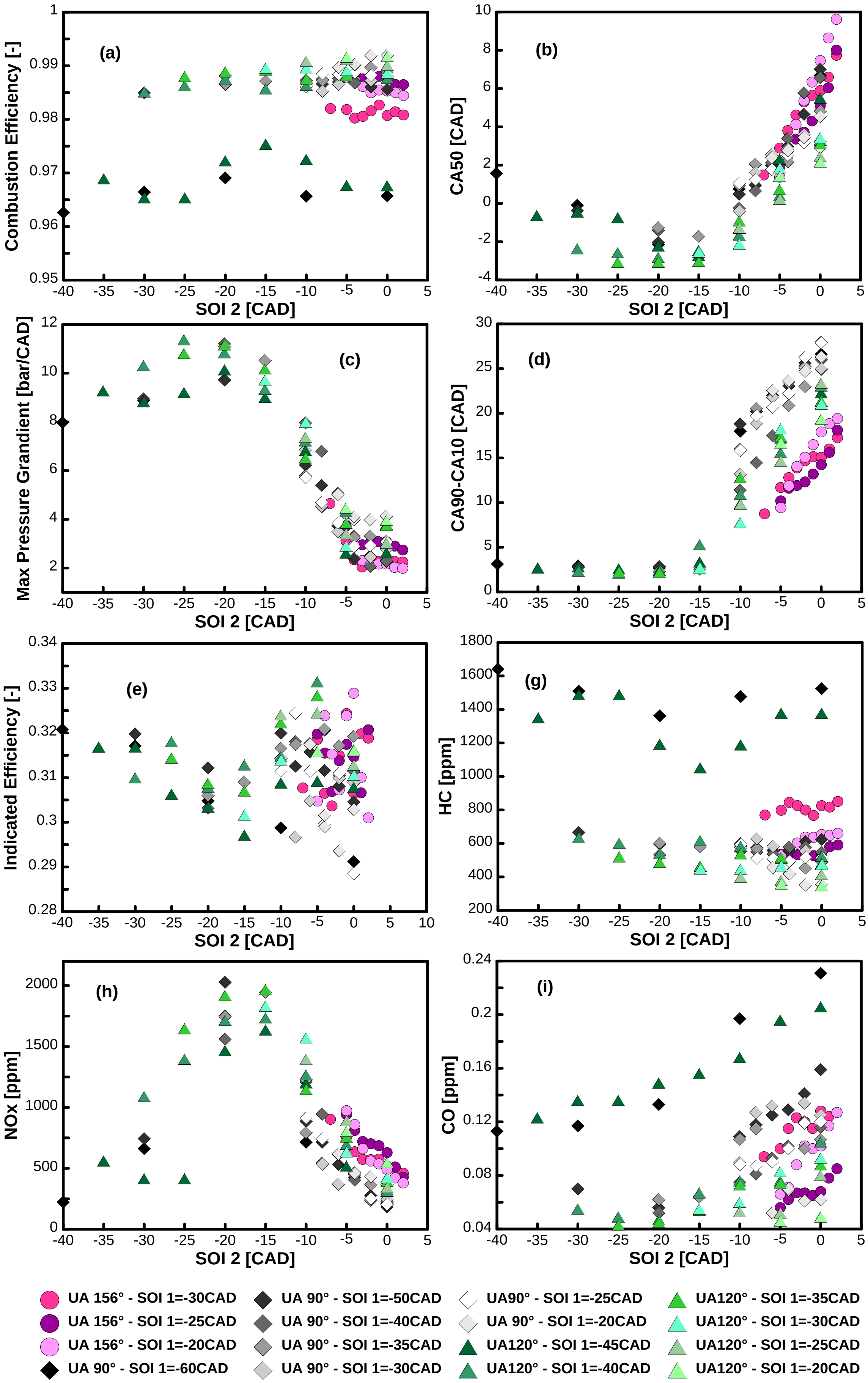

Figure 4 Combustion Parameters and Pollutant Emissions as a function of SOI1 and SOI2

combustion durations. However, longer combustion

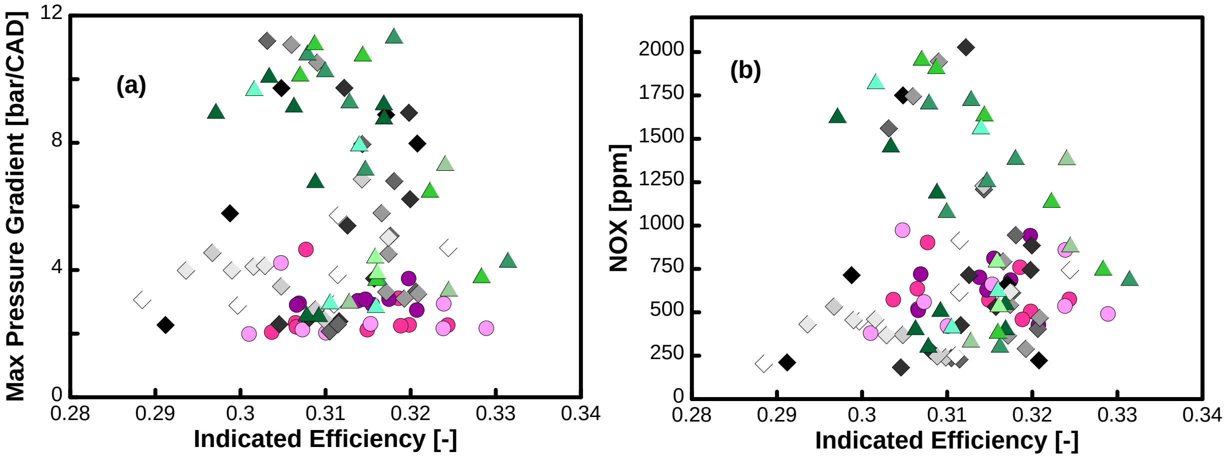

Figure 7: Max Pressure Gradient as a function of Indicated Efficiency (a). NOx emission as a function of Indicated Efficiency. Double Injection strategy for each of the injector tested.

have an impact on the indicated efficiency. In fact, observing Figure 8 (e), it could be observed that wider umbrella angle enabled faster combustion leading to improved indicated efficiency that for the UA156and UA120 injectors reached a maximum of about 33%. In Figure 8(f) and Figure 8 (g) are shown the results from the exhaust measurements of HC and NOx respectively. NOx emission are strictly related to the combustion phasing, so that NOx could be limited by delaying the second injection event. NOx emissions increasingly reduced when SOI2 moved towards TDC. Moreover, NOx emission resulted to be related to the umbrella angle: narrower spray trajectory led to reduced NOx emission, while the UA156 injector presented increased production of Nitrogen Oxide independently by the combustion phasing. Umbrella angle also impacted the production of unburned carbon. As shown in Figure 8 (g), unburned carbon could originate from the squish region when the first injection is too advanced (i.e. for SOI1=-60 and SOI1=-45CAD for the UA90 and UA120 cases respectively). Thus, delaying the first injection timing closer to TDC, allowed a strong reduction in HC emission. The narrower trajectory imposed by the UA120 and UA90 could help to concentrate the fuel air charge inside the piston head bowl leading to HC emission lower than 350 ppm, while the best results in the UA156 case originated at least 520 ppm of HC. In Figure 8(i) are reported the CO emission for the three injector tested. Trends shows that concentration of CO lower that 0.05 % can be achieved acting on the separation between the two injections when SOI 2 was close to TDC. In Figure 7 (a) and (b), In-Cylinder Pressure Gradient and NOx emission are shows as a function the Indicated Efficiency for the three different injector tested. Results indicated that for a fixed piston head geometry and at given intake conditions, the UA156 and UA120 offered better performance in terms of indicated efficiency while maintaining acceptable level of noise. On the other side, the UA90 injector showed the lower NOx emission value with a 1% point less of indicated efficiency if compared with the UA120 and UA156 injectors.

4. Conclusion

An_investigation into the impact of the injector's umbrella angle at low load operating conditions of a Direct-Injection GCI engine fueled with RON95 gasoline was performed in this work.

The first part of the study focused on understanding the impact of umbrella angle when a single injection of gasoline was performed over a wide range of injection timings. The umbrella angle defined the early limit of the SOI range, while the late limit depended on the fuel autoignition propensity and on the intake air thermodynamic conditions. Inside the SOI range, combustion behavior depends on the spray target position. If the same spray target position was obtained for the three injectors, pollutant emission and combustion behavior only slightly depended on the umbrella angle. Better results in terms of NOx and HC emission were obtained with a UA90 injector while the spray targeted the lower part of the bowl, while a UA120 injector offered better performance in terms of indicated efficiency. Autoignition of gasoline was then analyzed as a function of the start of injection, and results showed that at early injection timing, because of geometrical spray bowl interactions, high NOx production can occur. Part of the exhaust NOx can get trapped in to the residual burnt gases improving the autoignition propensity of gasoline, and leading to an abnormal advance in combustion phasing. At later injection timing, local distribution of the temperature and the equivalence ratio mainly drive the onset of combustion. Despite the low load operating conditions, higher pressure gradient were registered. In the second part of the work, a double injection strategy was performed. The SOI range could be extended because of the reduced amount of gasoline injected during the first injection event and because of fuel stratification enabled autoignition of gasoline even when the last injection toke place close to TDC. For the three injectors, the first injection timing mainly determined the combustion noise, HC and CO emissions, while the second injection event enabled the control over the combustion phasing, and NOx. The three different injector presented the same overall behavior, however, the UA90 injector presented better HC-NOx trade off while the UA120 and UA156 enabled improved noise-efficiency trade off.

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