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STUDY OF PARTICULATE MATTER AND GASEOUS EMISSIONS IN GASOLINE DIRECT INJECTION ENGINE USING ON-BOARD EXHAUST GAS FUEL REFORMING

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ABSTRACT

Gasoline Direct Injection (GDI) engines provide advantages over preceding spark ignition engine technologies in terms of reduced fuel consumption, increased power output and CO_2 depletion. However, the main drawback is the increased level of Particulate Matter (PM) emissions, which is associated with the adverse effects on human health and the environment.

GDI engine's fuel economy can further be enhanced by exhaust gas fuel reforming, a thermochemical recovery technique, which utilizes the engine exhaust gas heat, CO_2 and H_2O to produce a hydrogen-rich gas named reformate. Furthermore, additional benefits in gaseous emissions can be achieved through the combustion of reformate. In this investigation, a prototype on-board fuel reformer has been employed in a GDI engine to study the effects of reformate combustion as a supplementary fuel to gasoline on PM and gaseous emissions. Between 5-6% reduction in the engine fuel consumption was achieved by using the fuel reformer. The different effects (i.e. dilution, thermal, chemical, etc.) of the reformate combustion on the PM nature and gaseous emissions has been identified. It was found that the reformate combustion can decrease notably the engine PM emissions, however, the reduction is dependent on the PM nature. Reformate combustion was found to remove soot cores more efficiently than the volatile PM. The study has shown that the three-way catalytic converter (TWC) can reduce PM emissions. The possible interactions between the reformate and the TWC operation have also been analyzed. For the studied conditions, fuel reforming technology has not shown significant detrimental influence on the TWC operation.

Keywords: GDI, PM characterization, EGR, REGR, hydrogen, TWC, gaseous emissions.

1. INTRODUCTION

The multiple advantages of Gasoline Direct Injection (GDI) engines have positioned this technology as the current trend for gasoline powertrains [1, 2]. Amongst GDI benefits, the increased power output, and improved engine efficiency [1, 3, 4] are the most advantageous. Therefore, GDI engines are framed in the drive for more efficient technologies and in the reduction of anthropogenic greenhouse gas emissions from transportation. However, the major concern about GDI engines is the increased particulate matter (PM) emissions compared to their counterparts Port Fuel Injection (PFI) engines [5, 6]. PM composition can vary depending on the engine operating condition. In the case of stoichiometric GDI engine operation, with optimized fuel injection timing, the PM formed contains a low level of soot. However, there are some circumstances, such as in cold start operation, which could lead to higher rates of soot formation due to the large liquid fuel droplets formation and spray impingement. In the case of lean GDI engine operation, stratified charge promotes increased levels of soot as a result of the rich in fuel regions in the combustion chamber [7]. PM negative effects on human health and the environment have been broadly reported. In the work carried out by Jarvis et al [8], the carcinogenic and mutagenic behavior of polyaromatic hydrocarbons (PAHs) adsorbed in the carbonaceous core (soot) of PM is reported. Furthermore, researchers have provided evidence to link PM exposure to asthma and respiratory issues and cardiopulmonary morbidity and mortality [9-13]. As a result of the awareness of PM hazardous effects, upcoming legislation, such the European Euro 6c, will strictly limit the particulate number emitted to 6 x10^{11} #/km for GDI engines from September 2017.

Despite the technical advances in the automotive sector, still between 20-40% of fuel energy is wasted in the engine exhaust [14, 15] with a 6% exergy content available [16]. With the aim of improving overall engine's efficiency, different techniques for exhaust energy recovery have been broadly researched in the literature such as thermoelectrical generators [17, 18] and Rankine cycles [19, 20]. In addition to thermal recovery, catalytic techniques offer the possibility of utilizing products from engine combustion, water and CO_2. A fuel injection is required in order to produce endothermic reactions (thermal recovery) with CO_2 and water to produce hydrogen and CO (chemical recovery). Substantial efforts in reforming modelling have been made to understand the influence of the type of catalyst [21], C/O ratio [21] and reforming fuel type [22-24] on reforming pathways, hydrogen production and process efficiency. For instance, it has been concluded that in the case of short chain length alcohol fuels reforming lower temperatures are required when compared to gasoline due to the alcohols rapid and strong adsorption, high reactivity, high diffusivity, high H/C ratio and steric hindrance [25, 26].

Hydrogen combustion can lead to further advantages in engine performance and emissions. For example, its high diffusion coefficient, high flame speed and smaller quenching distance enhances the combustion, reducing both PM mass and number [16]. In addition, the presence of H_2 promotes the production of OH radicals, which reduces the soot formation rate [17] and enhances soot oxidation [18]. Hydrogen combustion could also raise the in-cylinder temperature, which can enhance PM oxidation [18] but at the same time can increase NOx emissions [19, 20]. Despite these benefits, safety reasons due to abnormal hydrogen combustion (e.g. surface ignition and backfiring) and the low energy density in terms of volume of hydrogen hinders its use in mobile applications due to well-known storage challenges [21, 22]. Therefore, exhaust gas fuel reforming could be a feasible approach to introduce hydrogen in transportation and overcome the challenge of hydrogen storage.

Reformed exhaust gas recirculation (REGR) has been extensively studied for diesel engines [27] and PFI gasoline engine using bottled reformer gas [28, 29] and plasmatron reformer [30]. Recently, the studies have also been extended to GDI engines [31] and benefits of simulated reformate have been compared to conventional EGR [32]. High rates of EGR in gasoline engines are currently under investigation as it reduces NOx emissions [33] and improves fuel economy [33-36] due to the reduced pumping losses [34, 37]. EGR worsens combustion stability which could be partially counteracted in the case of REGR by the hydrogen combustion within the REGR stream. Therefore, the combination of exhaust thermochemical recovery, EGR and hydrogen combustion could further reduce engine fuel consumption while maintaining combustion stability. In addition, the utilization of gaseous components (H_2, CO, CO_2 and HCs) as part of REGR leads to further advantages in the engine out gaseous emission [32, 38]. For instance, Ji et al [39] reported a 5%

increase in thermal efficiency when a 2.4% CO+H_2 was fed to the engine as well as a reduction in NOx and THC.

The overall effects of REGR in gasoline engines have been examined [32, 38] however, it is still not clear what are the independent effects of EGR and actual reformate combustion on engine performance and emissions including both gaseous and PM. Therefore, in this study, actual reformate has been produced in an on-board prototype exhaust gas fuel reformer incorporated in the EGR loop of a modern GDI engine. For first time, the effects of the high diluted REGR on fuel economy, combustion, gaseous emissions and especially on PM concentration depending on PM characteristics (composition and size) have been identified. It has been previously reported the presence of different PM types in the GDI exhaust [40, 41]. For this reason, two injection timings have been used as a tool to obtain the two types of PM, one with a high volatile organic material (VOC) nature and one with sooty nature. The independent effects related to REGR (dilution, thermal, chemical and spark timing) have been studied in isolation. Also, the effect over the three-way catalyst (TWC) was analyzed to find possible synergies or inhibitions between on-board reforming and conventional aftertreatment systems.

2. EXPERIMENTAL SETUP AND METHODOLOGY

2.1 Experimental setup

The engine used for this study is a stoichiometric 2 L, 4-cylinder, air-guided GDI engine. A steady state engine operation was selected: 2100±2 rpm and 60±1 Nm that corresponds to a low load mode: 4.7±0.3 bar indicated mean effective pressure (IMEP) representative of urban driving conditions. A Heated Exhaust Gas Oxygen (HEGO) sensor was used for oxygen measurement. The details of the engine specification can be found in Table 1. An AVL miniature piezo-electric pressure transducer model GM12D and a single channel piezo amplifier referenced to the engine cycle using a Baumer 720 pulse per revolution magnetic rotary encoder were used for in-cylinder pressure measurements. An average of 200 cycles was considered for in-cylinder pressure analysis. Fuel consumption was obtained with a Rheonik RM015 Coriolis fuel flow meter. Part of the OEM's engine strategy for NOx control is valve overlapping to increase the residuals (internal EGR) (intake valve opening timing 11 CAD bTDC, exhaust valve closing timing 57 CAD aTDC). The exhaust valve closing timing was modified to 8 CAD bTDC to avoid the influence of the internal EGR in PM and gaseous emissions. Standard EN228 gasoline with 5% (v/v) ethanol content provided by Shell has been used for this research. The same batch was used throughout this investigation. Fuel properties are presented in Table 2.

Table 1. Engine specifications.

Compression ratio	10:1
Bore x stroke	87.5 x 83.1 mm
Turbocharger	Borg Warner k03
Rated power	149 kW at 6000 rpm
Rated torque	300 Nm at 1750-4500 rpm
Engine management	Bosch ME17

Table 2. Gasoline properties.

Analysis (Test method)	Result
Density at 15ºC (kg/m^3)	743.9
IBP (ºC)	34.6
20% v/v (ºC)	55.8
50% v/v (ºC)	94.0
FBP (ºC)	186.3
C m/m (%)	84.16
H m/m (%)	13.48
O m/m (%)	2.36
Paraffins v/v (%)	43.9
Olefins v/v (%)	11.7
Naphthenes v/v (%)	7.8
Aromatics v/v (%)	26.9
Oxygenates v/v (%)	7.7
Sulfur (RFA) m/m (ppm)	6
Lower heating value (MJ/kg)	42.22
MON	85.3
RON	96.5

The aftertreatment system is composed of a commercial TWC which meets the Euro 6 legislation and an on-board reformer designed by Johnson Matthey consisting of five metallic plates coated with Pt–Rh based catalyst. For the reforming process, part of the exhaust gas flow before the TWC was diverted to the catalytic input of the reformer. In this stream, gasoline was injected for the reforming reactions. The rest of the exhaust stream was treated by the TWC and then used for the second inlet of the reformer to heat up the reforming catalyst. Heat exchange, but not mass exchange, is produced in the reformer between both exhaust gas streams, increasing the temperature of the catalyzed exhaust+gasoline stream and therefore, promoting endothermic reforming reactions between the gasoline and hot exhaust gas [31]. The reforming process products were mainly hydrogen and CO that are recirculated back to the engine intake. This process is known as REGR. A schematic of the engine reformer integrated system is shown in Figure 1 together with the experimental setup.

Legislated gaseous emissions (CO, CO_2, NOx and THC) were measured using a Fourier Transform Infrared Spectroscopy (FTIR) 2100 MKS. The exhaust gas was filtered to avoid possible damage to the optical lenses of the FTIR by the PM and pumped to the equipment. To prevent the condensation of HCs and water, in the heated lines, they were maintained at 190°C. The FTIR has been also spanned using known concentrations of CO_2, CO, NO and THC and a Horiba MEXA 7100DEGR gas analyser was used to remove experimental bias during this procedure. The lowest detection limits of the MultiGas 2030 FTIR analyser are 3.6 ppm for NO, 1.2 ppm for CO and lower than 1 ppm for the rest of species measured in this investigation.

Electrical mobility particulate size distribution (PSD) measurements were carried out using a TSI scanning mobility particle sizer (SMPS) composed by a series 3080 electrostatic classifier, a 3081 Differential Mobility Analyzer (DMA) and a 3775 Condensation Particle Counter (CPC). The sheath and aerosol flows were 10 and 1 liters per minute respectively. The upscan and downscan time were set to 90 and 30 seconds. PSD, for the parameters selected, ranges from 7.5 to 294 nm electrical mobility diameter The dilution ratio (DR) was set at

11 using an ejector diluter system to precondition the sample for the SMPS measurement. PSDs were evaluated before three-way catalyst (bTWC), after three-way catalyst (aTWC) and in the reformer output to analyze the possible formation of PM in the reformer.

The hydrogen production downstream the reformer was evaluated by an HP 5890 Series 2 gas chromatograph (GC) coupled with a thermal conductivity detector (GC-TCD) and HP 3395 integrator. The carrier gas was argon and the detector was calibrated with 30% hydrogen in nitrogen. All the gaseous emissions have been converted to humid exhaust flow conditions.

A schematic of the experimental setup is presented in Figure 1. The dotted lines represent the sampling points for the SMPS, GC-hydrogen and FTIR respectively.

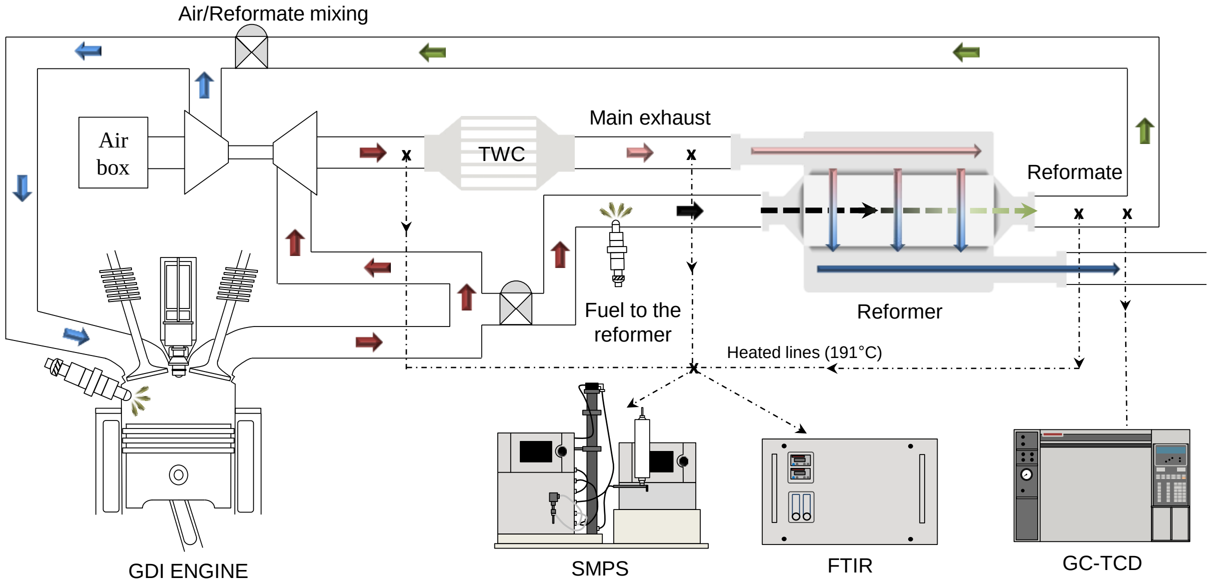


Figure 1. Schematic of the experimental setup.

2.2 Test procedure/Methodology

An analysis in fuel economy savings, combustion, PSD and gaseous emissions was carried out for high dilution rates of EGR and REGR at one steady state engine operation condition. As previously stated, one of the aims of this investigation is to examine the effect of EGR and REGR on PM nature. For this reason, two injection timings were analyzed which produced different PM nature: i) 303 CAD bTDC, the ECU injection, forming small nuclei and mostly VOC particulates and ii) 335 CAD bTDC, an advanced injection, producing highly sooty particulates due to the wall-piston wetting [42, 43]. The maximum percentage of EGR was used for the analysis being 19% and 24% for 303 CAD bTDC and 335 CAD bTDC, respectively. It was determined from the coefficient of variation (COV) of IMEP which was chosen to be lower than 5%. Conversely to 335 CAD injection timing, at 303 CAD injection timing the maximum EGR rate was limited by the pressure of the air stream (post-compressor) rather than combustion stability as larger opening values for EGR valve did not increase the EGR rate. At 335 CAD injection timing the combustion efficiency was lower with respect to 303

CAD injection timing (supported by the higher THC and particulate matter emissions), thus higher fuel and air mass flows to maintain the IMEP and lambda are required. It is thought that this increase in the flow through the compressor in the case of 335 CAD injection timing resulted in a lower pressure ratio through the compressor reducing the air pressure post-compressor and thus extending the capability of external EGR. The ST was adjusted to maintain the maximum position of in-cylinder pressure for EGR and REGR combustion in a ±3 CAD window with respect to the baseline maximum peak pressure position. As the set spark timings are different depending on the operating condition (see Table 3) a spark timing screening was performed to identify its contribution in the reformate net effect on combustion and emissions. The screening was carried out from the ST of the EGR until the set ST of the REGR. Samples before and after the TWC as well as in the reformer output were analyzed for all the studied conditions.

The tests were repeated for robustness and statistical analysis purposes. Confidence intervals using a 95% confidence level which reflects the reliability and repeatability of the experiments have been calculated based on the results of more than 9 measurements taken for each condition. Those confidence intervals include scan-to-scan and day-to-day variability in the operating condition and have been included where legibility of the figure is not much affected. Prior to the test, the engine was warmed up, and the measurements started when 95±0.5 °C coolant and 101±2 °C oil temperatures were reached. The air stream temperature was maintained at 40±2 °C during the experiment to reduce the test-to-test variability. Fuel injection pressure and fuel injection rail temperature were maintained constant at 60±2 bar and 75.5±0.5 °C, respectively for both injection timings.

Table 3. Baseline, EGR and REGR percentage analyzed and ECU settings (spark timing and maximum pressure peak position).

	Injection timing CAD bTDC	EGR (%)	Spark timing CAD	Targeted position max in-cylinder pressure (CAD aTDC)
Baseline	303	0	24 (ECU)	16
	335	0	24 (ECU)	12
EGR	303	19	+ 8.25(*)	16
	335	24	+ 17.25(*)	12
REGR	303	19	+ 3.75(*)	16
	335	24	- 0.25(*)	12

(*) + advance, - retard, spark timing with respect to ECU settings.

The reformate composition, on humid base, for both injection timings is presented in Table 4. Approximately 5% hydrogen production was measured at both injection timings for steady state conditions. The small difference in hydrogen levels for each injection may be due to the different gas hourly space velocity through the reformer. However, the H_2/CO ratio is slightly higher for 335 CAD (H_2/CO = 2.4) compared to 303 CAD (H_2/CO = 2.2) injection timing. It is suggested that this is due to a higher utilization of the water present in the exhaust (either via steam reforming or/and water gas shift) than CO_2 (dry reforming) for the reformate production.

Table 4. Reformate composition.

	H_2 (%)	CO (%)	CO_2 (%)	H_2O (%)

303 CAD bTDC	5	2.7	11	9
335 CAD bTDC	4.35	1.6	10.5	10.3

3. RESULTS AND DISCUSSION

3.1 Combustion parameters

Table 5 shows the combustion parameters obtained from in-cylinder pressure for both fuel injection timings for the noEGR, EGR and REGR operation. The IMEP was maintained constant at 4.7 bar and the COV of IMEP remained below 5% for all the conditions tested to assure stable combustion. The application of REGR enables retarding the ST while maintaining the same IMEP as well as reduces the COV of IMEP for all the spark timing tested with respect to EGR as a result of the high diffusivity and flame speed of hydrogen. As the ST was adjusted to maintain similar peak pressure position for baseline, EGR and REGR combustion, a screening was performed to identify the influence of ST in in-cylinder pressure trace, gaseous emissions and PM. This screening was carried out from the ST of the EGR until the original ST of the REGR condition. It can be observed that maintaining the position of the maximum peak pressure leads to lower peak pressure for the REGR condition. The same trend is obtained for both injection timings, being more noticeable for 335 CAD bTDC as the ST variation range was wider.

Table 5. Engine combustion parameters.

Injection timing	Dilution	Spark timing (CAD bTDC)	COV of IMEP (%)	IMEP	Position Pmax (CAD)	Pmax (bar)
303 CAD bTDC	noEGR	+ 24 (ECU)	2.03	4.7	16	27
	EGR	+ 32.25 (+ 8.25*)	4.35	4.71	16.5	25.28
	REGR	+ 32.25 (+ 8.25*)	4.63	4.7	14	24
		+ 27.75 (+ 3.75*)	3.33	4.62	15	25.37
335 CAD bTDC	noEGR	+ 24 (ECU)	1.2	4.71	12	31.37
	EGR	+ 41.25 (+ 17.25*)	5.22	4.69	13.5	28
	REGR	+ 41.25 (+ 17.25*)	3.25	4.61	11	28.64
		+ 33 (+ 9*)	1.73	4.68	13	27.35
		+ 23.25 (- 0.75*)	2.97	4.63	15	23.5

(*) + advance, - retard, spark timing with respect to ECU settings.

3.2 Engine fuel consumption and energy efficiency

The brake specific fuel consumption (BSFC) for the two injection timings was recorded at the three conditions (noEGR, EGR and REGR). Fuel consumption is reduced by 3% when EGR is used for both injection timings. This fuel economy benefit with the use of EGR is mainly attributed to the reduction of pumping losses [35, 36], heat loss to the cylinder walls and the degree of dissociation occurring at high temperature burned gasses [37]. In addition, EGR can contribute to further fuel economy improvement at full load as a replacement of the fuel enrichment technique used to mitigate knock [34]. The addition of the reformate into the EGR loop while keeping the same spark timing settings as in the case of EGR decreased total fuel consumption. Moreover, when the ST is modified under the presence of the reformate gas further improvements up to 5-6% in fuel economy are achieved. This percentage also takes into account the quantity of the fuel that was used in the reforming process (around 10% of the total fuel consumption). BSFC for REGR at 335 CAD bTDC is slightly higher than for the 303 CAD bTDC gasoline fuel injection timing. It is believed that as the EGR rate permitted by the engine is larger for 335, the gas hourly space velocity in the reformer is higher. Thus, the reforming process is less efficient when compared to 303 CAD bTDC injection timing (the ECU settings). As has been previously stated, this study has been done maintaining the dilution level and the peak of the maximum pressure constant to fairly compare EGR and REGR effect in gaseous and PM emissions. However, REGR combustion operation could be optimized (further rates of REGR are tolerated by the engine as the combustion stability is increased), resulting in an extra reduction in fuel consumption if reformer process efficiency is not significantly deteriorated [38].

3.3 Particulate Matter analysis at high diluted REGR conditions

The REGR and EGR effects on PSD for both fuel injection timings are presented in Figure 2. The measurements were taken before and after the TWC in order to analyze the performance of the TWC in PM.

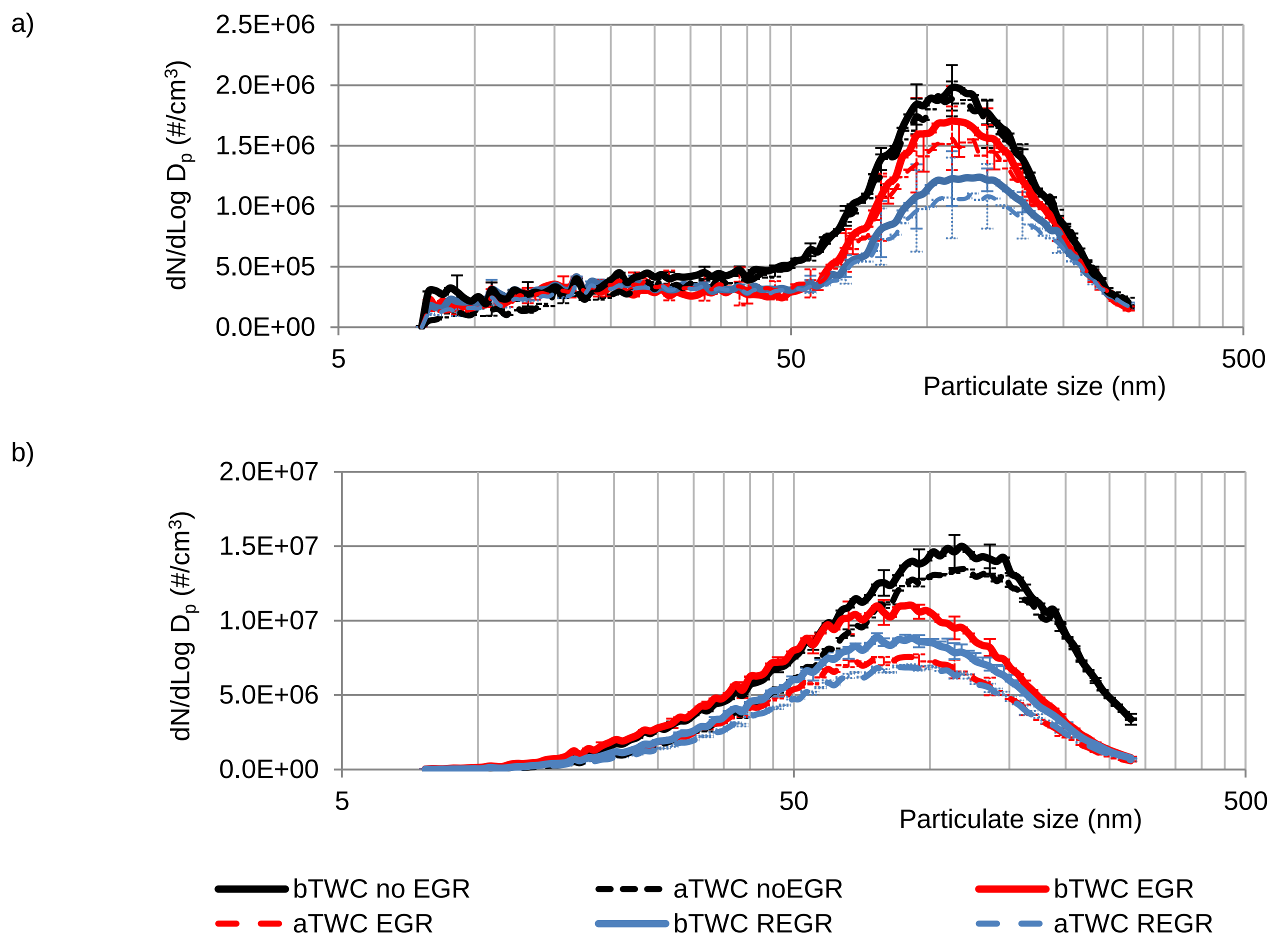


Figure 2. Effect of TWC on PSD for baseline, EGR and REGR operating conditions at a) 303 CAD bTDC injection timing and b) 335 CAD bTDC injection timing.

Independently of the injection timing, the REGR is able to reduce significantly PM with respect to baseline and EGR combustion. At 303 CAD bTDC, this reduction is produced vertically along the whole distribution, being able to reduce even the concentration of small size particles. At 335 CAD bTDC, the PSD is further reduced but shifted to lower diameters (lower mean electrical mobility particulate size). Those results have several implications. They suggest, the reformer combustion prevents the formation of soot cores reducing the probability of collision and agglomeration of particles leading to a reduction in the agglomerate diameter, while a different growing mechanism for 303 CAD bTDC injection timing (volatile nature PM) occur as the reduction in the particle number concentration does not decrease the agglomerate size. These results also help to identify the different nature (based on composition) of the particulates emitted under 303 degree BTDC injection timing which have larger sizes compare to 335 CAD bTDC injection timing even though the particulate concentration is much lower. This is because at 303 CAD bTDC injection timing the growing mechanism of the agglomerates is mainly through the adsorption and condensation of volatile material to soot nuclei being the final agglomerate size independent of particle number concentration. The production of smaller size particles in the case of EGR and REGR compare to baseline combustion could be seen as a drawback as smaller particles can penetrate deeper into the respiratory system, they present higher reactivity (the ratio surface-volume is greater) and remain a longer time in the atmosphere. However, the reduction of the mean particulate size with REGR combustion is not due to an increase in the number of small particles but an important reduction in the number of large particles. Therefore, the concentration of particles for mobility diameters lower than 60 nm remained the same or even reduced being beneficial for the environment and human health. The different effects associated with REGR combustion which influences PM emissions are discussed below.

In order to maintain the same fuel/oxygen ratio for EGR and REGR operation with respect to the baseline condition, an increase in the mass of the inducted in-cylinder charge is required. This higher in-cylinder charge results in lower in-cylinder oxidant concentration [37] which promotes soot formation and slows down soot oxidation (dilution effect) but also reduces the in-cylinder temperatures inhibiting soot formation and oxidation (thermal effect). The higher hydrogen and CO concentration in REGR with respect to EGR and baseline combustion improves engine fuel economy and increases in-cylinder pressure and thus combustion temperature when the same spark timing is selected. Improved engine fuel economy also leads to a higher liquid fuel replacement by the reformate gas. As a result, the reductions of both local rich in fuel regions [38] and the overall carbonaceous content of the fuel inhibits soot precursors formation and growth. The increase in the in-cylinder temperature promotes PM formation and growth [31] and assists in HCs and PM precursor oxidation [38]. Furthermore, hydrogen inhibits soot nucleation [44] and promotes soot and soot precursors oxidation through the OH radical [45, 46]. On the other hand, the high recirculation of CO, in the case of REGR, reduces the oxygen and OH concentration available for soot oxidation to CO_2 [46]. In addition, the recirculation of particles within the EGR loop could increase engine output PM emissions [44, 45].

For first time, the effect of the reformer catalyst in the formation and/or removal of particles has been investigated. PSDs were sampled upstream and downstream the reformer (Figure 4). At 303 CAD bTDC, the concentration of small particles is reduced in the reformer, while no effect is shown for particles larger than 55 nm. On the other hand, at 335 CAD bTDC, the particle distribution is reduced across the PSD range. Therefore, it can be concluded that the reformer does not act as a new source of PM and there is a certain but limited PM trapping effect by diffusion in the reformer catalyst.

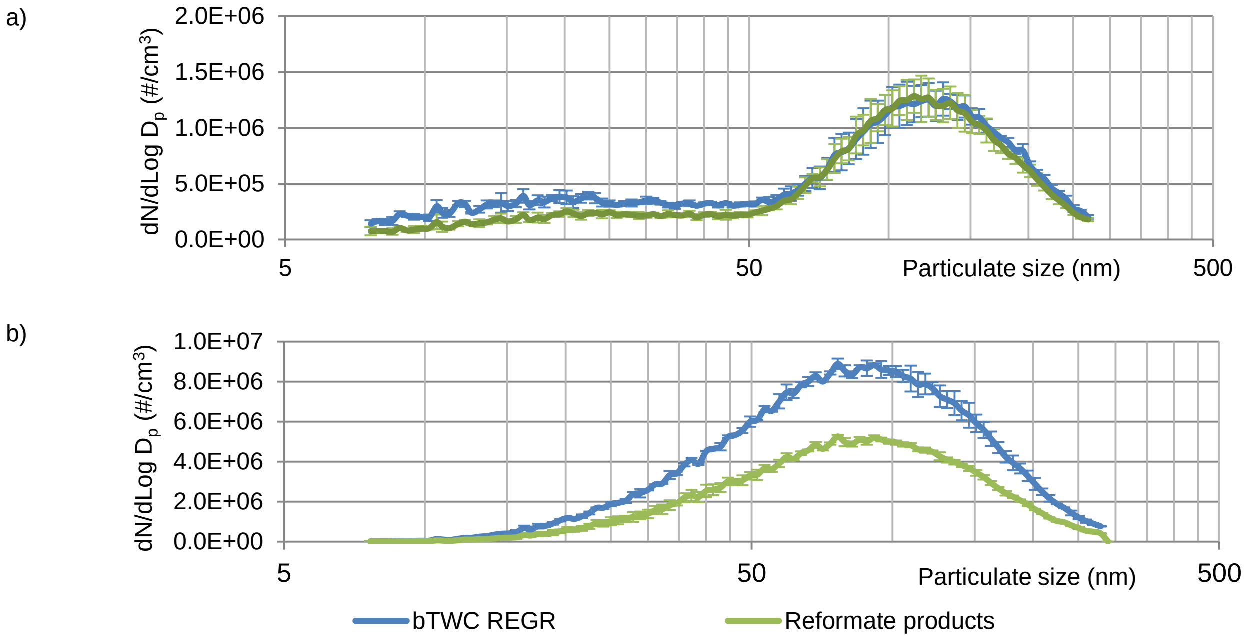
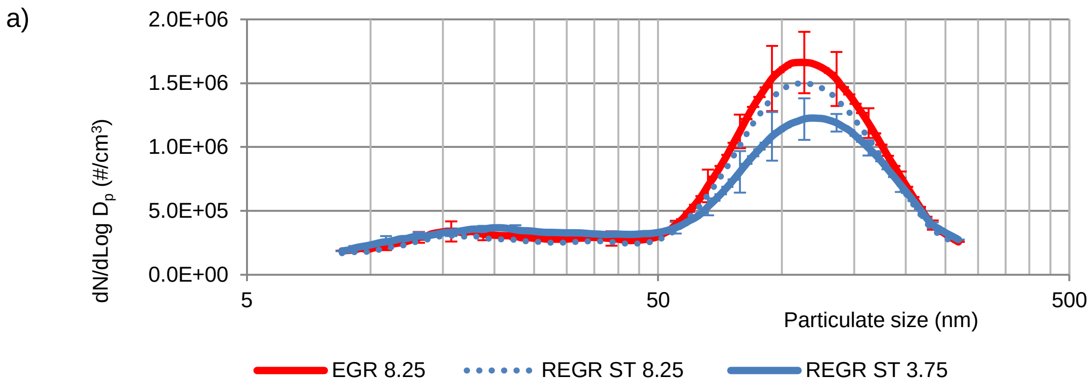


Figure 3. Effect of reformer on particulate size distributions at a) 303 CAD bTDC injection timing and b) 335 CAD bTDC injection timing.

The effect of spark timing on PM emissions has been also independently studied although no dependences are reported [46]. In Figure 4 as the spark timing is retarded the PM concentration is slightly reduced, especially the accumulation mode. Therefore, the advanced spark timing for EGR with respect to baseline hinders the EGR beneficial effects on PM. In the case of REGR combustion, as the particle emissions are lower compared to EGR at the same spark timing, as REGR operation permits retarding the spark timing, PM emissions are further reduced. The reduction of PM for retarded spark timings is attributed to the increase in the available time for fuel-air mixturing [47-49] and better fuel combustion efficiency associated to the retard in ST which compensates the possible inhibition on soot oxidation due to the lower combustion peak temperatures when spark timing is retarded [50].



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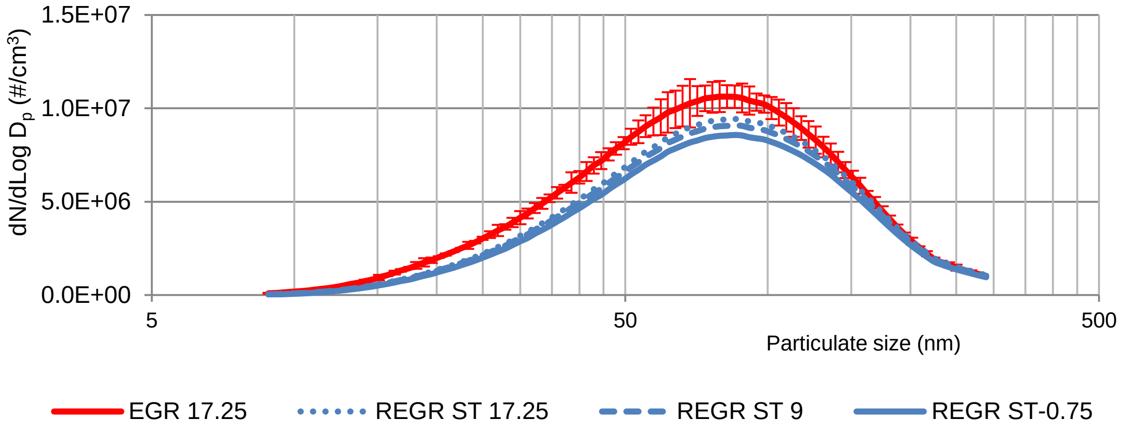

Figure 4. Effect of spark timing on particulate size distributions at a) 303 CAD bTDC and b) 335 CAD bTDC.

The relative importance of the different effects described above (i.e. dilution, thermal, chemical, etc.) depends on the EGR/REGR rate, the PM nature and level of soot formation and oxidation which are influenced by the fuel injection timing. For instance, in the case of a very advanced injection timing (335 CAD bTDC) the PM reduction of REGR with respect to EGR is more significant. It is thought that this is mainly due to the higher impact of the chemical effects of hydrogen on “diesel-like” soot production conditions when there is a higher presence of locally rich in fuel regions (e.g. piston wetting and pool fires) and the proportion of condensed/adsorbed hydrocarbons onto PM is lower. The contribution of those effects on PM is shown in Table 6.

The TWC reduces PM at advanced injection timing when most of the particulates consist of solid soot cores. However, the TWC had no effect on PM produced at 303 CAD bTDC fuel injection timing, opposed to the expected higher reduction due to the volatile nature of the PMs. The results suggest that those particulates are composed of HCs which are unable to be controlled in the TWC either by oxidation or filtration. Furthermore, the size of the particles for both injection timings is not significantly modified by the catalytic converter. Therefore, it seems that the TWC is just acting as a filter, trapping some solid particles deposited in its channels by diffusion. Further oxidation of those trapped particles is expected due to the high catalyst temperatures.

Table 6. Qualitative effects of EGR and REGR with respect to baseline condition performance in GDI engines.

EGR	**PM**		**NO**		**CO**		**THC**	
Injection timing	303	335	303	335	303	335	303	335
Dilution effect	↑↑	↑↑	↓↓	↓↓	↑	↑	↑	↑
Chemical	↓↑	↓	↓	↓	↓	↓	↑	↑
Thermal	↓↓↓	↓↓↓	↓↓↓	↓↓↓	↓↑	↓↑	↑	↑
Inlet temperature	↑	↑	↑	↑	↑	↑	↑	↑
Liquid fuel replacement	↓↓	↓↓	Minor effect	Minor effect	↓↓	↓↓	↓↓	↓↓
Spark timing	↑	↑	↑↑	↑↑	Minor effect	Minor effect	↑	↑
PM recirculation	Minor effect	Minor effect	No effect	No effect	No effect	No effect	No effect	No effect
Net Effect	↓	↓↓	↓↓↓	↓↓↓	↓	↓	↑	↑

REGR	**PM**		**NO**		**CO**		**THC**	
Injection timing	303	335	303	335	303	335	303	335
Dilution effect	↑↑	↑↑	↓↓	↓↓	↑	↑	↑	↑
Chemical	↓	↓↓	↓↑	↓↑	↓↓↑	↓↓↑	↑	↑
Thermal	↓↓	↓↓	↓	↓	↓	↓	↓	↓
Inlet temperature	↑	↑	↑	↑	↑	↑	↑	↑
Liquid fuel replacement	↓↓↓	↓↓↓	Minor effect	Minor effect	↓↓	↓↓	↓↓	↓↓
Spark timing	Minor effect	Minor effect	Minor effect	Minor effect	Minor effect	Minor effect	Minor effect	Minor effect
PM recirculation	Minor effect	Minor effect	No effect	No effect	No effect	No effect	No effect	No effect
Net Effect	↓↓↓	↓↓↓↓	↓↓	↓↓	↓↓	↓↓	≈	≈

3.4 Gaseous emissions analysis at high diluted REGR condition

The level of engine out gaseous emissions and their confidence intervals before and after the TWC for all the conditions studied are plotted in Figure 5. EGR and REGR are able to significantly reduce CO and NO concentration levels when compared to baseline operation for both fuel injection timings. In the case of REGR, such reductions are around 30% and 90%, respectively. REGR also reduces CO_2 concentration with respect to the baseline, but the differences are within the confidence interval limits. It has to be noted that the results are shown in concentration. In the case of CO_2 emissions (in terms of g/kWh or g/km) the effects of EGR and REGR would be more significant as the reduction in the exhaust mass flow will be also taken into account.

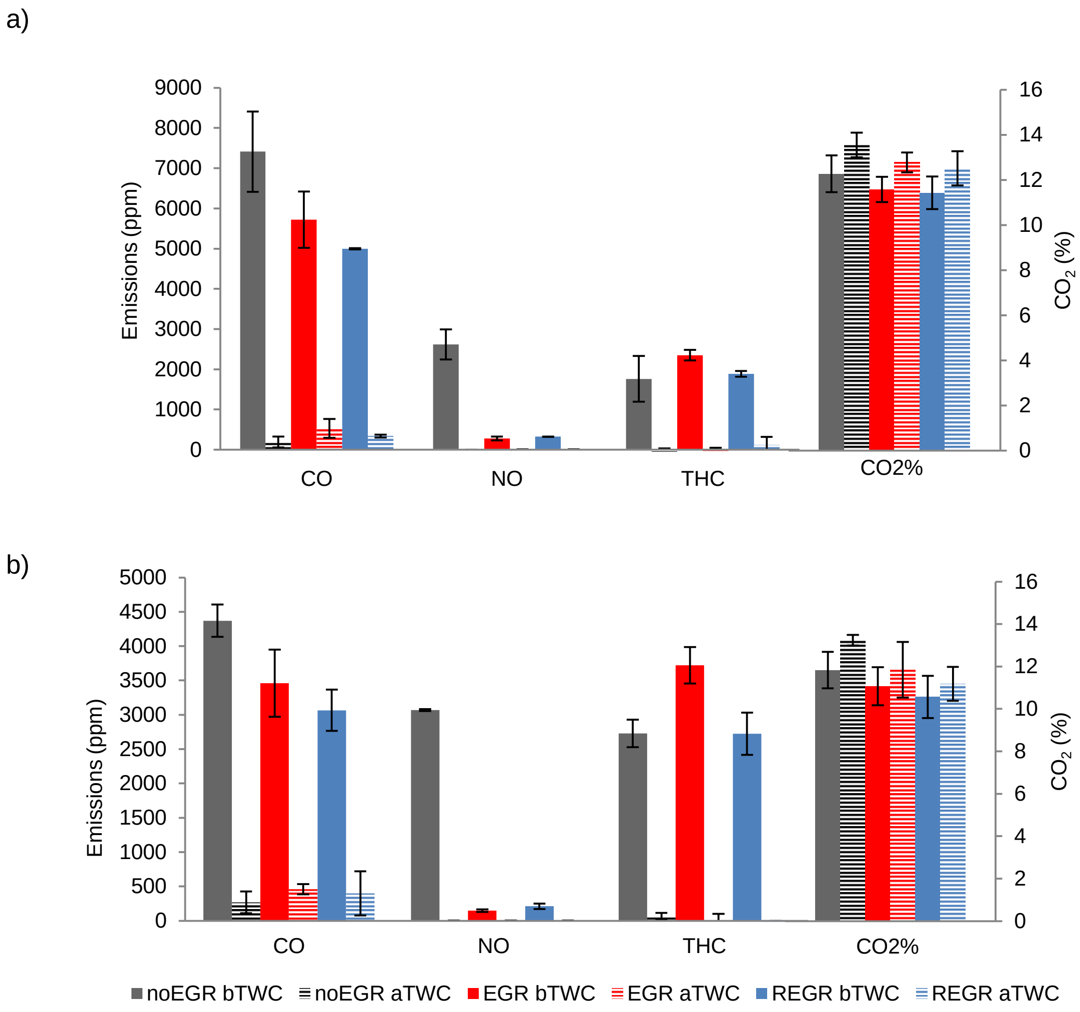

Figure 5. Engine gaseous emissions for baseline, EGR and REGR before and after TWC at a) 303 CAD bTDC and b) 335 CAD bTDC.

As REGR operation allows the use of retard ST, a ST sweep was performed in order to separate its effect in gaseous emissions and PM. Figure 6 shows the average variation rate of CO, THC and NO with respect to the EGR together with their confident interval. The screening starts from the ST of the EGR to the ST set for REGR based on peak pressure timing. CO and THC for REGR combustion are reduced when compared to the EGR independently of the ST value, while NO emissions are generally higher for REGR. At 303 CAD, the emission differences between STs are not significant as they are within the confidence interval. However, at 335 CAD, where the screening window is larger the effects are more noticeable. CO concentration presents a bath-tube shape curve for 335 CAD bTDC where the ST is widely varied. It is thought that when ST is slightly retarded, the reduction in liquid fuel consumption resulted in a decrease in CO emissions, but when it is further delayed, the increase in the available time for mixture formation and the reduction of in-cylinder pressure and temperature enhanced incomplete combustion resulting incomplete combustion of HCs to CO emissions. THC levels are reduced when the ST is retarded to the set REGR ST. It is believed that the improvements in fuel consumption as well as the larger available time to homogenize the fuel-air mixture counteract the lower in-cylinder temperature when the ST is retarded resulting in a progressive decrease of THC. The trends of NO for both injection timings are similar but are more significant in the case of 335 CAD bTDC injection timing that the ST window is wider (Figure 6). The main reason for such reduction in NO is the lower in-cylinder pressure and temperature owned to the retarded ST. It has to be noted that lower NO concentration under REGR with respect the EGR combustion can be achieved when the ST is retarded to the set value.

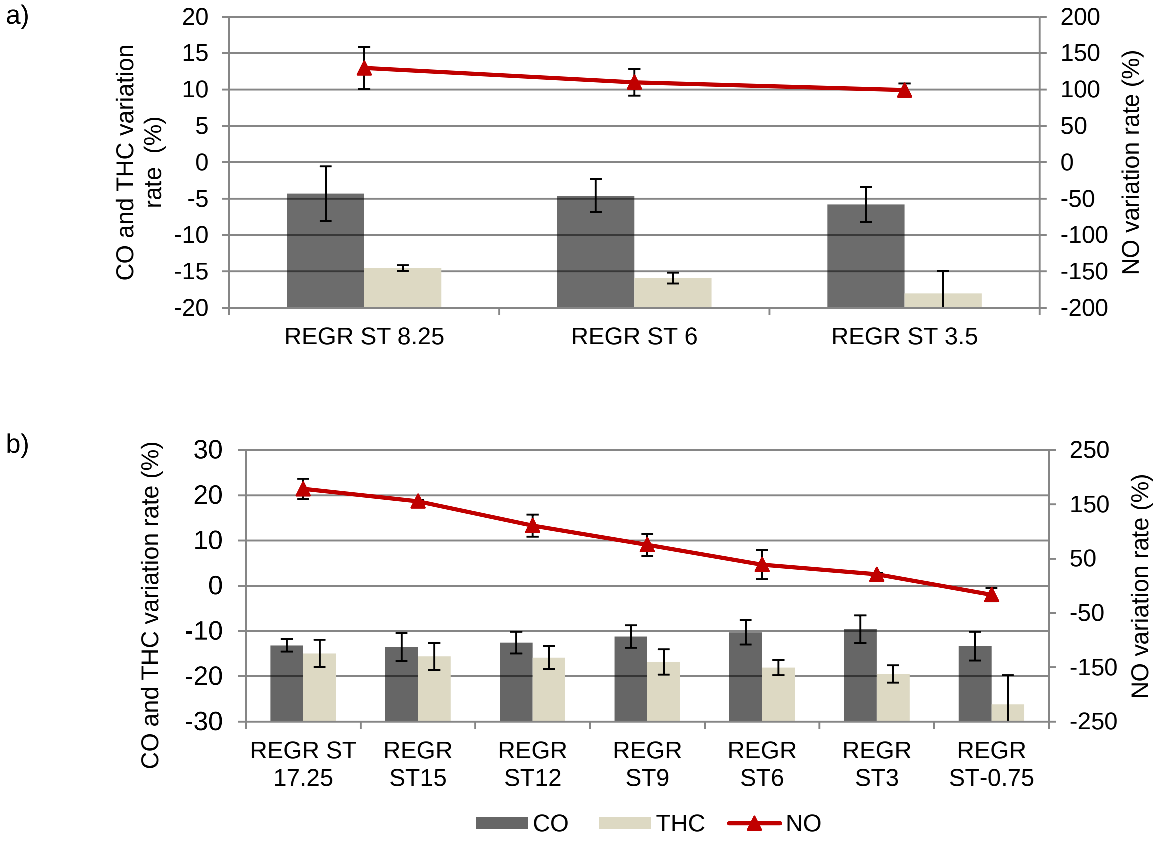

Figure 6. Effect of spark timing on gaseous emissions under REGR conditions at a) 303 CAD bTDC and b) 335 CAD bTDC.

The larger reduction in engine out CO_2 level with REGR in comparison to EGR is due to the presence of fuels with lower carbon content (e.g. hydrogen) as well as due to the utilization of part of the recirculated CO_2 in the reforming process.. The decrease in engine CO emissions with EGR in respect to baseline combustion is mainly due to the reduction in liquid fuel utilization because of the improved thermal efficiency as a result of the reduction in pumping losses. This results in shorter liquid fuel injection duration and small concentration of hydrogen, CO and other gaseous HC species being recirculated within EGR loop. When REGR is applied further benefits in CO emissions are obtained (see Figure 5) even though high concentration of CO is produced in the reformer and thus introduced to the engine cylinder. It is believed that the larger decrease in CO when REGR is combusted is due to the larger reductions in liquid fuel combustion, higher concentration of hydrogen which is combusted and efficient oxidation of CO in the combustion process. No significant difference is observed for THC behavior between baseline and REGR combustion. However, REGR is advantageous compared to EGR as the impact in increasing the THC emissions is significantly lower (Figure 5). It is suggested that the beneficial chemical effects of hydrogen, spark timing (in the case of 335 CAD bTDC injection timing) and larger liquid fuel replacement of REGR with respect to EGR are the responsible factors of the lower THC level of REGR with respect to EGR. The engine out emissions of NO for EGR and REGR are significantly lower compared to the baseline condition (Figure 5). It is reported that the dilution effect (the increase of the total in-cylinder mass reduces the concentration of both oxygen and nitrogen in the combustion chamber) and the lower local in-cylinder pressure and temperature in the combustion chamber hampers the gas phase reaction to produce NOx emissions. On the other hand, in the case of REGR, H_2 combustion leads to local higher temperature in the combustion chamber compared to EGR, thus increasing NO emissions. However, it can be seen that NO levels are markedly reduced, below the EGR emission, when the ST is retarded enough. As in the case of PM emissions, the effects on gaseous emissions of the different studied variables are showed in Table 4. Therefore, the application of REGR enables retarding the ST while maintaining the same IMEP reducing NOx emissions (see Figure 7) without any detrimental effect on engine efficiency. As in the case of PM emissions, the effects on gaseous emissions of the different studied variables are showed in Table 6.

The performance of the TWC is also analyzed in Figure 5. No difference in THC and NO emission reduction can be observed with EGR and REGR with respect to the TWC operation under baseline combustion operation. Nevertheless, the oxidation of CO is slightly worsened with REGR and especially with EGR combustion as a consequence of the lower availability of NO upstream of the three way catalyst to catalytically oxidize the HCs and CO within the catalyst.

4. CONCLUSIONS

The use of catalytically on-board fuel reforming in gasoline direct injection engines has been studied. Benefits in fuel economy, gaseous carbonaceous emissions and PM have been obtained. The reformate effects over gaseous emissions and PM have been in depth studied and the sources of the reformate benefits have been isolated.

The reduction in liquid fuel consumption as a result of the replacement of gasoline by the reformate products and the improvements in fuel efficiency as well as the chemical effects of hydrogen are the major reasons of the carbonaceous gaseous emissions and PM reductions with the use of on-board REGR. The utilization of part of the recirculated CO_2 to produce hydrogen in the reformer enables to reduce even further the CO_2 level emitted to the atmosphere. The reduction in the in-cylinder temperature due to the higher mass of intake charge (dilution effect) and the possibility to maintain spark timing similar to the baseline condition while keeping combustion stability provide the significant NOx reduction with REGR combustion compared to baseline.

It can be concluded that REGR is a technique which is able to extend the benefit of using EGR in GDI engines. Further benefits are also obtained due to the synergies in combustion stability, reutilization of the in-cylinder produced CO_2, gaseous emissions and PM which are a global major concern due to its pernicious effect on human health and the environment, from the combination of the higher mass of intake charge (EGR) and the presence of hydrogen in the reformate products. Those benefits should be further investigated varying fuel composition as well as in non-steady state engine operating condition and even on-board the real vehicle.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

aTWC	After Three-Way Catalyst
bTWC	Before Three-Way Catalyst
bTDC	Before Top Dead Centre
BSFC	Break Specific Fuel Consumption
CAD	Crank Angle Degree
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COV	Coefficient of Variance
CPC	Condensation Particle Counter
DR	Dilution Ratio
ECU	Electronic Computer Unit
EGR	Exhaust Gas Recirculation
FBP	Final Boiling Point
FTIR	Fourier Transform Infrared
GC-TCD	Gas Chromatograph - Thermal Conductivity Detector
GDI	Gasoline Direct Injection
HCs	Hydrocarbons
IBP	Initial Boiling Point
IMEP	Indicated Mean Effective Pressure
MON	Motor Octane Number
NEDC	New European Driving Cycle

NOx	Nitrogen Oxides
PAHs	Polyaromatic Hydrocarbons
PFI	Port Fuel Injection
PM	Particulate Matter
PSD	Particulate Size Distribution
REGR	Reformate Exhaust Gas Recirculation
RON	Research Octane Number
SMPS	Scanning Mobility Particulate Analyzer
ST	Spark Timing
THC	Total Hydrocarbons
TWC	Three-Way Catalyst
VOC	Volatile Organic Material

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