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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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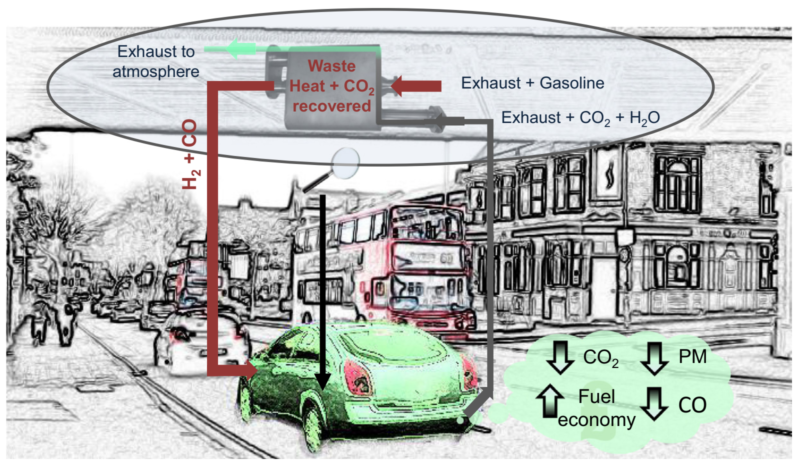
HIGHLIGHTS

- The effect of on-board reformate on PM with different nature has been characterized for GDI engines.
- A study categorizing the reformate effects on PM and gaseous emissions has been carried out.
- Fuel economy and CO_2 emissions have been reduced in 5–6% with a prototype on-board reformer.
- It has been proven that the reformer does not act as an extra-source of PM production.
- A longer residence time in the three way catalyst is required to oxidize PM.

GRAPHICAL ABSTRACT



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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% and 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

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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TWC
Gaseous emissions

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.

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 studied. 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 particle number emitted to 6×10^{11} #/km for GDI engines from September 2017.

Despite the technical advances in the automotive sector, still between 20% and 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 extensively 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 formation 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 engines 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 they lower 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, 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 high diluted EGR/REGR on engine fuel economy, combustion characteristics, gaseous emissions and most importantly on PM emissions have been identified. The presence of different PM types (soot cores similar to diesel and "slurry-like" particles) has previously been seen in the GDI exhaust [40,41]. Depending on the nature of particles the effects of hydrogen combustion, REGR or EGR can be different. 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