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Impact of bio-alcohol fuels combustion on particulate matter morphology from efficient gasoline direct injection engines

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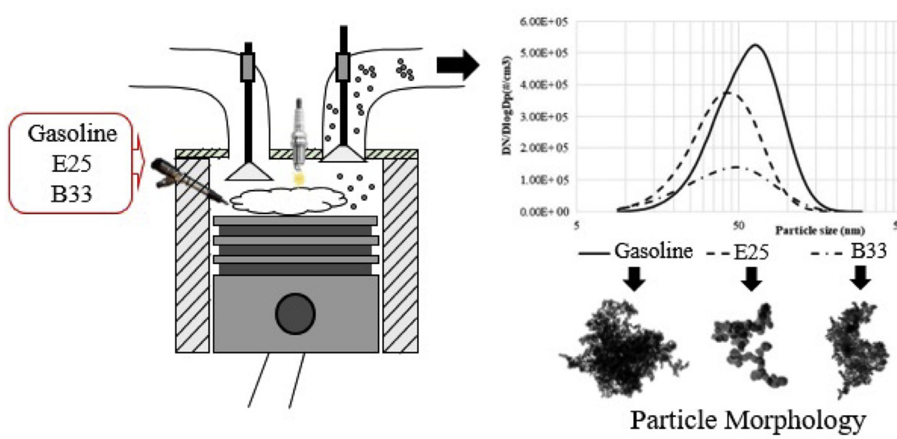
HIGHLIGHTS

- Bio-alcohol fuel properties on GDI engines affects morphological characteristics of particles.
- E25 & B33 fuel blends emitted smaller primary particles than gasoline combustion.
- B33 combustion significantly reduced particle emissions with respect to gasoline.
- B33 & gasoline formed larger agglomerates than E25 combustion.
- E25 emitted more like-chain particles than B33 and gasoline engine operation.

GRAPHICAL ABSTRACT



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ABSTRACT

The requirements for controlling particulate emissions in gasoline direct injection (GDI) engines, particularly in hybrid vehicles (where frequent cold-start event impact on both, particles characteristics and catalytic aftertreament efficiency), nesesitates the need for understanding their formation mechanism and their morphological characteristics. The findings described in this investigation have significance in the design of efficient Gasoline Particulate Filters (GPFs) and the development of computational models that predict particle filtration and oxidation processes.

Morphological analysis of the particulate emissions from the combustion of commercial gasoline and two bio-alcohol blends: of 25% v/v ethanol in gasoline and 33% v/v butanol and 67% v/v gasoline, in a modern GDI engine has been carried out using a transmission electron microscopy. The primary particle size distribution from the combustion of butanol-gasoline blend was slightly smaller compared to gasoline, while the mean primary particle diameter was 3 nm smaller from the combustion of ethanol-gasoline fuel. This decrease in primary particle size for ethanol-gasoline blend was also reflected in a reduction of the mean radius of gyration and mean number of primary particles per agglomerate.

The combustion of butanol-gasoline blend induced improved particle oxidation rates during the combustion process and post-oxidation stage, and led in 80% and 60% reduction in particle concentration in the engine

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exhaust when compared to the combustion of gasoline and ethanol-gasoline blend, respectively. Additionally, the estimation of the particle fractal dimension through the use of fractal equation, minimum bonding rectangle method and root form factor showed comparable results for butanol-gasoline and gasoline, with the particle agglomerates being more compact than the ethanol-gasoline fuel, where more chain like particles are seen. Therefore, particles emitted from the combustion of ethanol-gasoline fuel are easier to be trapped (lower fractal dimension) and present a higher reactivity (high surface/volume ratio) compared to particles emitted from gasoline combustion.

1. Introduction

Gasoline Direct Injection (GDI) engine technology enables a reduction in both vehicle fuel consumption and CO_2 emissions [1]. On the other hand, there is an increased production of particulate matter (PM) emissions, particularly during engine cold start and vehicle acceleration [2]. Under such conditions the fuel direct injection process is reported to lead to inhomogeneity of the air-fuel mixture and consequently incomplete fuel combustion, resulting in increased formation of soot [3]. Earlier studies have concluded that particulates in GDI engines are formed due to (i) the locally fuel rich regions during the combustion process even in homogeneous mixtures at the macro scale [4], (ii) piston wetting that leads to wall fuel-film formation as a consequence of the fuel injection process [5] and, (iii) the carbonisation of non-combusted fuel droplets [6,7]. Factors affecting soot formation are highly related to the chemical structure and thermo-physical properties of the fuel used in combustion process, in addition to local equivalence ratio and in-cylinder temperature.

The Euro 6c regulation restricts the emissions of the particulate number in gasoline engines to 6×10^{11} #/km and therefore, several techniques and strategies have been investigated to reduce the level of particulates in GDI vehicles. For instance, the use of exhaust gas recirculation (EGR) in GDI engine has shown reductions of about 20% [8] in overall particulate concentration as a result of the improved fuel economy (i.e. less fuel injected) due to the reduced pumping losses. Gasoline particulate filters (GPFs) can also control particulate emissions, with reported filtration efficiencies of 96–97% for particles below 10 nm [9] and up to 84% of filtration efficiency during the new European driving cycle (NEDC) [10]. Another alternative to reduce particle emission is the use of alternatives fuels. Bogarra et al. [11] and Fennell et al. [12] studied the effect of hydrogen produced in exhaust gas fuel reforming on particles formation in GDI engines. Both the replacement of liquid fuel and the combustion improvements by the addition of hydrogen inhibited particulate formation rates across a wide size range.

The inclusion of oxygenated bio-alcohol fuels in gasoline fuel can reduce PM emissions formation and enhance oxidation during the combustion process. Ethanol and butanol have been proposed as the next generation low-carbon fuels for transportation [13,14]. The chemical properties of bio-alcohols have been found to be beneficial for reducing PM emissions due to the absence of aromatics, which are potential source of PAHs (polycyclic aromatic hydrocarbons) and soot precursors [15]. In addition, the oxygen content in their molecules promotes particle oxidation and inhibits particle formation rates [16,17]. However, the literature suggests that the trend of PM emissions formation from the combustion of ethanol-gasoline blends is dependent on the percentage of the ethanol used in the fuel blend and the engine operating (speed/load) conditions. For instance, the higher heat of vaporisation and the low vapour pressure of ethanol can lead to a poorer evaporation compared to gasoline, and therefore, lower quality of air/fuel mixture [18]. The effect of E10 and E20 combustion on the particle size distribution of a wall-guided GDI engine was analysed by Luo et al. [19]. At low engine load conditions, the combustion of the ethanol/gasoline blends increased both the particle number (PN) and the mean diameter by around 20%. Subsequent increase of the engine load led to 20% reduction in PN and a significant decrease of 20 nm in particle size compared to gasoline. At high engine load conditions, the combination of fuel born oxygen and improved spray pattern of bio-alcohol fuel blends as consequence of the higher fuel injection pressure improved the air/fuel mixture and particulate emissions. Under these conditions the bio-alcohol fuel blend's chemical properties (i.e. oxygen content or low aromatic concentration) predominate over the fuel's physical properties (i.e. higher viscosity). Similar results are reported by He et al. [20] where the combustion of E20 at high engine load of 9 bar IMEP, reduced PN concentration by 20% compared to commercial gasoline. In contrast to the impact of ethanol/gasoline fuel blends on engine out PM emissions, butanol/gasoline blends have shown more consistent trends. Butanol/gasoline blends (B20) have been reported to reduce the concentration of large particles (40–60 nm), but results in the increased concentration of smaller particles 30 nm, with a reduction in the overall total number of particles by 40% [21]. Lattimore et al. [22] also found a significant reduction on particles larger than 50 nm using B20 fuel blend, while a reductions in PN of up to 80% was reported by Hergueta et al. [8] using a B33 fuel blend. The authors attributed this result to the fuel's lower aromatic concentration and higher oxygen content.

In addition to particle size distribution (PSD), transmission electron microscope (TEM) techniques have been used for morphological characterisation. Particle morphology can influence the filtration and regeneration processes of the GPF with an impact on the exhaust backpressure and engine fuel efficiency. Additionally, the porosity and permeability of PM are related to the primary particle diameter and the number of primary particles per agglomerate [23], which directly affect their oxidation reactivity. Primary particle diameters can also provide understanding of the soot oxidation rate as it is dependent on the aggregate surface area to volume ratio. It has been estimated that the aggregate surface area to volume ratio is inversely proportional to primary particle diameter [24]. Physico-chemical properties of biofuels (i.e. ethanol, butanol) are different with respect to gasoline and may modify the PM morphology and alter the soot accumulation and oxidation processes in the GPF. There is a limited number of work to report PM morphology in GDI engines. Recently, M. Bogarra [4] studied PM morphology using baseline gasoline, EGR and hydrogen at engine control unit (ECU) settings and when the fuel injection timing was advanced. Higher PM variability in primary particle diameters at ECU engine calibration was observed with a mean value of 29 nm for gasoline, while Uy et al. [25] and La Rocca et al. [26] observed different mean values of dp_0, being 23 nm and 36 nm, respectively. Barone et al. [27] investigated the influence of the fuel injection timing on PM morphology using a blend of E20. The average primary particle diameter was found to be around 25 nm and ranged between 8 and 52 nm when the injection timing was advanced (i.e. 325 CAD bTDC from 303 CAD bTDC). The primary particle diameter was reduced to around 10–15 nm when the fuel injection timing was retarded, but the range was widened when compared to advanced fuel injection timing (i.e. 7–60 nm). Similar results were observed by Lee et al. [28] in combustion studied with E20 with fuel injection timings ranging between 220 and 310 CAD bTDC.

The characterization of PM formed in GDI engines is still a subject under investigation in the automotive sector, especially when integrated within the hybrid vehicles where frequent stop starts are required. Understanding the particle characteristics is a key step for the development of efficient GPFs and accurate computational models in