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Investigation on the effects of butanol and ethanol fueling on combustion and PM emissions in an optically accessible DISI engine

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ABSTRACT

Generalization of direct injection and use of alternative fuels in spark ignition engines, are two trends that require detailed analysis of specific phenomena. Within this context, the present investigation was aimed at improved understanding of the effects of fuel injection phasing and engine speed on the emission of nanoparticles. Measurements were performed on a wall guided power unit with optical accessibility, that was fueled with gasoline, ethanol and butanol. Thermodynamic results were combined with exhaust gas measurements, particle size distribution and cycle-resolved imaging. The characterization was executed with stoichiometric fueling, for three different start of injection settings during the intake stroke. Engine speed effects were evaluated during slightly lean operation, so that spark timing could be maintained fixed for all trials without the occurrence of abnormal combustion. Visualization of flame front propagation and localized diffusive oxidation induced by unevaporated fuel, allowed the observed variations in engine performance and emissions, to be correlated to liquid film distribution within the combustion chamber. Changes were found to be minor for gasoline when injection phasing was modified, while the alcohols featured noticeable sensitivity. A major effect was observed on the emission of particles, more so for butanol. Through the complete characterization of thermodynamic, exhaust and visualization data, the mechanism of fuel jets impinging on the combustion chamber walls was identified as the main influence. The alcohols' higher latent heat of evaporation and low saturation pressure were recognized as determining fuel properties that induced the observed changes.

1. Introduction

Recent worldwide legislation enforces the increased use of fuels from renewable sources and the simultaneous reduction of greenhouse gas (GHG) and pollutant emissions. These targets are highly challenging in the automotive field and can determine contrasts in the implementation of development strategies. If spark ignition (SI) engine technology is considered, the combination of direct injection and turbocharging, together with the help of new lightweight materials that lower overall vehicle weight, provides the cost effective means to reduce fuel consumption and carbon dioxide (CO_2) emissions [1–3]. On the other hand, if direct injection (DI) SI power units are compared to port fuel injection (PFI) engines, they emit higher concentrations of particulate matter (PM) [4–6]. Direct injection of the fuel into the combustion chamber can induce incomplete evaporation, especially during cold start. Impingement of droplets onto piston and cylinder walls is another unwanted effect; these lead to locally rich, diffusion-governed liquid fuel combustion or pyrolysis that is prone to PM formation. Thus, more care is needed for the design and calibration of DI combustion systems, so as to maintain low PM emissions and to meet stringent future standards [7–9]. Changes in the fuel composition represent a valid solution to reduce GHG emissions. Blending bio-alcohols (ethanol or butanol produced by renewable means) with gasoline allows a decrease of petroleum consumption and fossil-based CO_2 emissions [10,11].

The pros and cons of n-butanol compared to ethanol have been discussed in several works [12–14]. In terms of ecological properties, both alcohols can be produced from non-edible biomass; the main advantages of butanol are related to the higher energy density and better blending ability [15]. Also, n-butanol is less hygroscopic and corrosive [16] and it can be used in the fuel distribution lines without specific precautions. However, n-butanol is currently less competitive in term of price [12,17], mainly because of the relatively low production efficiency and high recovery costs in the acetone-n-butanol-ethanol (ABE) or isopropanol-n-butanol-ethanol (IBE) fermentation processes, which are current bio-n-butanol production methods.

The effect of bio-alcohol fuels on performance and exhaust emissions has been widely investigated for indirect [18–23] and direct

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injection [15,16,24–34] SI engines. Few of the works on DISI engines were focused on neat butanol or ethanol use [15,29–35]. In terms of exhaust emissions, experiments on DISI engines showed that indicated specific CO concentrations decreased as the ethanol percentage in the blend with gasoline increased [29]; the effect was justified by the oxygen content in the fuel molecule that facilitated the oxidation of CO to CO_2. On the other hand, the reduction was observed only in a specific range of spark advance at fixed injection timing; outside this range, for more advanced ignition the mixing time was reduced, causing an increase in CO emissions, due to lower combustion efficiency. Conversely, retarded spark timing reduced in-cylinder temperatures and the efficiency of CO oxidation. When pure ethanol was injected in stoichiometric conditions, CO emission increased with load [30]. A similar effect was observed for butanol fueling, that showed an increasing difference in CO concentration at the exhaust with respect to gasoline when the engine switched from low to medium load [31] and then to wide open thottle (WOT) conditions [32]. For both alcohol fuels, exhaust CO concentration resulted strongly influenced by the injection timing due to the dependency on the local fuel/air equivalence ratio; in particular, it sharply increased in fuel rich regions [29,32]. Even if stoichiometric conditions were considered, charge stratification in the DI combustion chamber was related to the spray characteristics and fuel volatility property. Piston and cylinder wall wetting induced liquid fuel films that affected the level of homogeneity. Gasoline had advantages over alcohol fuels in CO emissions due to its volatility properties and higher energy density, that lead to shorter injection time and reduced fuel spray penetration [36]. It should be noted that since the ethanol fuel molecule is more ‘oxygenated’ compared to butanol, more oxygen is available for complete combustion; this contributes to a better counterbalance of the disadvantage caused by piston and liner wall wetting, thus reducing the emission of CO.

Higher content of oxygen in alcohol fuels supports oxidation and can also reduce the total unburned-hydrocarbon (THC) emissions. An almost linear decrease in HC emissions with the increase of ethanol content was measured [29], even if a significant dependence on spark timing was observed. Specifically, the hydrocarbon emissions increased at advancing ignition timing, because a greater mass of fresh charge was trapped in the crevice volumes, and its oxidation was less effective due to the lower temperature in the exhaust stroke. For neat butanol and ethanol, HC emissions were strongly related to the injection timing and load, as consequence of the improvement of fuel evaporation [30,33]. Alcohols showed lower HC compared to gasoline, even if more fuel impingement on the piston and cylinder liner was present, given their lower boiling point that ultimately promoted evaporation near the walls.

If NO_x emissions are considered, a slight increase was recorded with respect to gasoline, when using low ethanol [29] or butanol [27] blending ratios. The effect was reduced when sweeping from part to full load. On the contrary, at high alcohol concentrations (higher than 50%), a general reduction in NO_x emissions was measured with DI, both in homogenous [26,28,32] and stratified conditions [37] due to the enhanced mixing of combustion-product gases with excess air that contribute to low NO formation rates. It was observed that NO_x emissions of ethanol blends are higher than those containing n-butanol, but lower than those of gasoline, as a result of lower in-cylinder temperature and oxygen enriched environment [28].

Finally, regarding particulate matter, several works investigated the effect of oxygenated fuels blended with gasoline on in-cylinder particle formation and relative exhaust emissions, by considering both optical [32,33,37,38] and commercial DISI engines [34,39]. On the other hand, few works treated simultaneously the effect of butanol and ethanol fueling [39,40] and practically none investigated the effects of neat alcohol fueling [32,33,41]. As a general result, it was observed that an increase in ethanol addition in stoichiometric mixtures and cold start cases, determined an increase in both particle number and mass of fine particles, due to the deleterious effect of ethanol on spray break-up and evaporation caused by the high vaporization enthalpy and low energy density [41]. On the other hand, for warm engine conditions, working at rich and stoichiometric air-fuel ratio [42], in part load as well as full load [43], adding ethanol strongly reduced PM emissions, due to the fact that the presence of oxygen in the fuel molecule reduced concentrations of key intermediate species required for the formation of soot precursors. Part-load tests demonstrated that the variation in injection timing closely affected particulate number (PN) emissions [43]; in particular, strong retardation of start of injection (SOI) reduced the time required to form a homogeneous air-fuel mixture and induced an increase in PM emissions. On the other hand, the advance from the optimized phasing caused wall-wetting phenomena on the piston head and cylinder wall, and hence negatively affected particle emissions. Similar results were obtained for butanol; in particular, it was demonstrated that the alcohol fuel induced considerably less PM emissions due to significantly lower soot formation resulting from their oxygen content [40]. Moreover, PN emissions from gasoline fueling were mainly from the accumulation mode. With increasing alcohol content, the total concentration remarkably decreased, even if number density due to alcohol blends was higher in the nucleation mode [33]. Similarly to ethanol fueling, the injection timing resulted a critical point for the reduction of PM due to the decrease in the evaporation efficiency [32].

Starting from these considerations, this paper discusses the effect of injection timing on in-cylinder particulate formation and successive particle exhaust emissions of a DISI engine. Gasoline, n-butanol and ethanol fueling was investigated through optical techniques, with the aim of contributing to a complete understanding of the effect of oxygenated fuels on the combustion process. Particular interest was devoted to the diffusive flames induced by oxidation of unevaporated fuel within the combustion chamber. Based on cycle-resolved imaging data, the morphological parameters of these flames were investigated and the fuel injection strategies are also analyzed with respect to size distribution of the fine and ultrafine particles at the exhaust. All tests were performed on an optically accessible wall guided SI engine under different settings of injection phasing in WOT conditions, with stoichiometric air-fuel ratio. The effect of the engine speed was investigated as well, during lean operation, so that spark timing could be maintained constant for all measurements without the risk of knock. Compared to previous investigations [32,33], the work is focused on the difference between the two alcohols and the effect of engine speed. The actual analysis of size and spatial distribution of the diffusive flames is also more statistically oriented, with added details on the correlation between fuel properties and observed changes in engine performance, evaluated based on measured in-cylinder pressure. The data recorded during combustion was coupled with exhaust gas measurements and characterization of particle number distribution.

2. Material and methods

2.1. Engine

An experimental campaign was organized and effected for studying the influence of ethanol and butanol's properties on combustion and emissions. The optically accessible power unit (Fig. 1) allowed visibility into the combustion chamber from below via a Bowditch design [44]. Engine specifications are listed in Table 1 (with CAD for crank angle degrees, a for after and b for before top dead center (TDC)). Geometric compression ratio was set at 10 for this study; no attempts were performed for optimizing this parameter for each fuel, even though significant benefits could be obtained in this sense, especially for ethanol, given its high octane rating [45]. As illustrated in Fig. 1, one of its main features is the commercial cylinder head adapted for the engine block that houses the elongated piston. The automotive engine from which the head was taken had a four valves per cylinder configuration, with centrally located spark plug and side mounted wall guided injection; more details on the six hole injector and the specifics of jet-wall