Effect of ethanol blends on soot formation and emissions in a GDI optical engine

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Abstract
Gasoline direct injection (GDI) systems were introduced to improve fuel economy and decrease the emissions of greenhouse gases. On the other hand, GDI engines are negatively characterized by large emissions of particulate matter (PM) emissions. The use of oxygenated fuels, such as ethanol, can help in reducing particulate emissions, thus allowing facing the challenges to meet future emissions standards.
This study explores the influence of ethanol on particulate matter formation and emissions in GDI engines. Experimental investigation was carried out in an optical 4-stroke cylinder engine. The engine displacement was 250 cm^3. It was equipped with an elongated piston with a wide sapphire window in the head and a quartz cylinder liner. The engine was fuelled with neat gasoline and ethanol, and ethanol/gasoline blends at 20% v/v, 50% v/v and 85% v/v. Measurements were carried out at different engine speeds and loads in order to perform a comprehensive study of soot formation in GDI engines. Optical techniques based on 2D-digital imaging were used to follow the combustion process and soot formation. Particle emissions were characterized in terms of number concentrations and size distribution using a differential mobility particle sizer.

Introduction

The gasoline Direct-Injection Spark-Ignition (GDI) engine has many well-known advantages over the port-fuel injected engine, such as the significant potential fuel economy benefits and the greater charge cooling potential. This latter allows higher engine compression ratios and then the increasing of the thermal efficiency [1]. One of the drawbacks is the increase in particulate emissions [2]. The use of oxygenated biofuels can represent the most viable solution to meet the future emission standards. Ethanol is the most suitable for spark ignition engines as it is an octane enhancer and it can be used both net and blended with gasoline.
Previous studies on ethanol effect on soot formation carried out on diffusive flames showed that the addition of small quantities of ethanol to gasoline has little effect on these flame properties [3]. Nevertheless, it was also observed that the effect of ethanol blends on particle emissions depends by the fuel volatilization and mixing as well as by the combustion chemistry [3, 4].
In order to perform a comprehensive study of the effect of ethanol blends on soot formation and emissions, optical measurements into the cylinder and conventional measurements at the exhaust were carried out in a small displacement transparent

single cylinder GDI engine. The engine was fuelled with neat gasoline and ethanol, and ethanol/gasoline blends at 20% v/v, 50% v/v and 85% v/v. Tests were carried out at 2000 rpm full load and 4000 rpm partial load. These engine points were chosen as representative of urban driving conditions. Moreover, they were characterized by different thermo fluid-dynamic conditions. High-speed 2D-digital imaging measurements were performed. These measurements allow following soot formation and oxidation processes. Particle size distribution function was measured in the range form 5 nm to 1000 nm by means of a Differential Mobility Spectrometer (DMS).

Experimental apparatus and procedures

The investigation was carried out on an optically accessible 4-stroke single cylinder SI engine. It was equipped with the cylinder head of a naturally aspirated GDI engine with a displacement of 250 cm^3. The engine head has four valves and a centrally located spark plug. The engine is equipped with an elongated piston with a wide flat sapphire window in the head and a quartz ring replacing the upper part of the cylinder liner. Engine specifications are shown in Table 1.

Table 1. Engine specifications.

Cylinder volume [cm^3]	250
Bore [mm]	72
Stroke [mm]	60
Compression ratio	10.5
Max power [kW]	16 at 8000
Max torque [Nm]	20 at 5500

The engine was fuelled with neat gasoline (E0) and ethanol (E100) and three blends 20%v/v (E20), 50%v/v (E50) and 85%v/v (E85) of ethanol in gasoline. The main fuels properties are listed in Table 2.

Table 2. Main chemical and physical properties for ethanol and gasoline fuel.

Fuel property	**Ethanol**	**Gasoline**
Oxygen [mass%]	34,7	2,7
LHV, MJ/l	21.1	30–33
RON/MON	108,6/92	98/87
Stoichiometric air/fuel	9	14,7

Figure 1 shows the optical set-up. The injection and combustion phases were visualized through the wide sapphire window located in the piston head. A UV-visible mirror inclined at 45 degrees and located in bottom of the engine reflects the in-cylinder images toward the optical detection assembly. A CCD camera equipped with a 50 mm focal length, f/3.8 Nikon lens was used to investigate the temporal and spatial evolution of flame. 2D flame emission intensity was correlated to the soot amount in the combustion chamber applying the two-color pyrometry theory [5]. The synchronization of the CCD camera with engine motion was driven by the crank angle encoder signal through a delay unit.

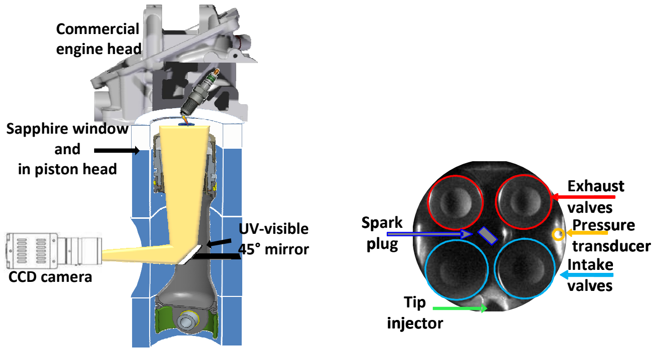

Figure 1. Optical setup and field of view of the combustion chamber.

Exhaust particle emissions were characterized in terms of number concentration and size distribution using a Differential Mobility Spectrometer (Cambustion DMS 500). The DMS500 operates a classification of the particles according to their electrical mobility diameter in the size range 5-1000 nm. It has a fully integrated two-stage dilution sampling system, providing the primary dilution at the point of sampling to avoid condensation and agglomeration issues, and a high ratio secondary dilution to allow sampling from a very wide range of aerosol concentrations. The measured particulate concentration is automatically corrected for the applied dilution. The 5 m heated line was used for the sampling of the engine exhaust in order to avoid condensation of combustion water.

Results and discussion

Several engine operating conditions were investigated in order to evaluate the effect of ethanol on particle formation and emissions under different thermo-fluid dynamic conditions. The spark timing was set to operate at the maximum brake torque. The duration of injection increases at the increasing of the ethanol content in order to operate always in stoichiometric conditions. A sequence of combustion images at 2000 rpm and full load, representative of the different combustion phases, is depicted in figure 2.

Bright spots are detected before the flame front reaches the chamber walls. These yellow bright spots can be due to the radiance of soot particles in the combustion chamber formed from the combustion of fuel rich zones due to residual droplets and incomplete air-fuel mixing. Once the flame front has reached the wetted surfaces, is observed a wide luminous sooting flame due to the diffusion controlled combustion of fuel films [6, 7]. Soot particles that are formed late in the expansion stroke largely contributes to PM emission as they are scarcely oxidized, because of lower temperatures, lack of oxygen and lesser time available for their burning.

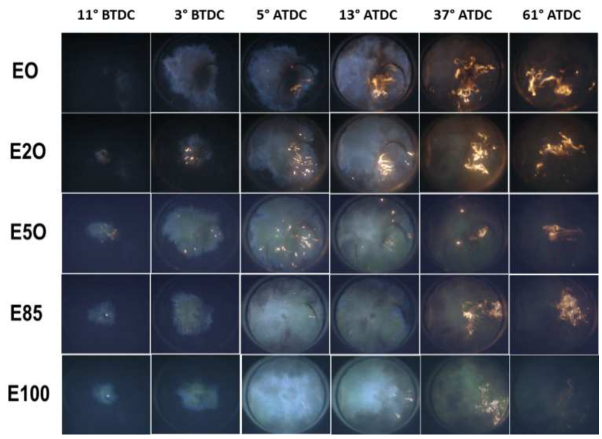

Figure 2. Selection of combustion frames for the tested fuels at 2000 rpm full load.

The effect of ethanol on soot formation and oxidation is evidenced in the integral visible luminosity of combustion depicted in figure 3.

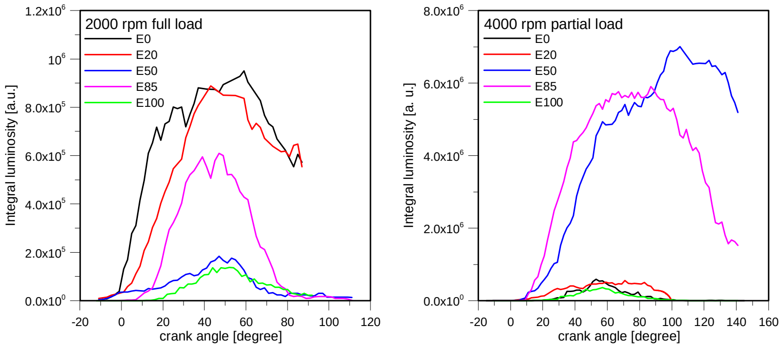

Figure 3. Integral luminosity for the tested fuels at 2000 rpm and 4000 rpm.

The effect of the ethanol on the total soot amount formed in the combustion chamber is not linear. At 4000 rpm partial load, in fact, a larger amount of soot is formed for E50 and E85 fuelling. Nevertheless, for E85 soot oxidation is more evident. These results are in good agreement with exhaust measurements. In figure 4 the particle size distribution, averaged over the whole sampling time, for all the tested fuels is shown.

The particle size distribution appears bimodal, whatever the fuel or the operating regime. At 2000 rpm and full load the nuclei mode greatly dominates the particle size distribution and is centered around 10-15 nm. The mean size and number concentration of particles in the accumulation mode decrease almost linearly with the ethanol percentage in the blend because of the sooting reduction tendency of oxygenated compounds [8-9].

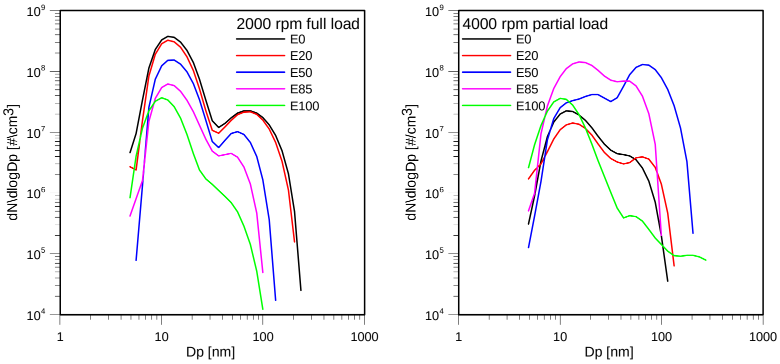

Figure 4. Particle size distribution for the tested fuels at 2000 rpm and 4000 rpm

At 4000 rpm and partial load, the exhaust PM does not follow this linear behavior. In particular, ethanol/gasoline blends emit a larger amount of particles than gasoline in the accumulation mode. The different behaviour can be explained considering that at 4000 rpm the early fuel injection timing leads to a significant fuel impingement. Moreover, the addition of gasoline significantly affects the evaporations of the blends [10-11]. Ethanol forms, in fact, a near-azeotropic mixture with the lighter compounds of gasoline hydrocarbons. In particular, the evaporation of lighter compounds of gasoline is greatly enhanced by ethanol addition, and the residual fuel will mainly contain heavier and highly sooting hydrocarbons. Fuel films will continue to burn late in the expansion stroke and in a colder environment. Therefore, it can be argued that ethanol addition creates extremely favorable conditions for the formation of soot particles from the heavy compounds of gasoline. These results suggest that the effect of ethanol on soot formation and emissions is strongly affected by fuel volatization and mixing.

Conclusions

An experimental investigation on the effect of blends of ethanol and gasoline fuel on the soot formation and emission was performed on a GDI optical engine. The engine has been operated at 2000 rpm full load and 4000 rpm partial load. It was fuelled with gasoline (E0), ethanol (E100) and blends 20% v/v (E20), 50% v/v (E50) and 85% v/v (E85) of ethanol in gasoline. Soot formation process was studied using imaging and two-color pyrometry, through a CCD color camera. Digital imaging results highlight the presence of some bright spots likely due to the radiance of soot particles. A wide luminous sooting flame due to the diffusion controlled combustion of fuel films is observed when the flame front has reached the wetted surfaces. Two-color pyrometry was applied in order to assess the space and time distribution of the soot into the combustion chamber through the analysis of the integral luminosity of the flame. The in-cylinder results are in good agreement with the particle size distribution measured at the exhaust. The particle size distribution is strongly affected by the fuel properties and the operative condition. At 2000 rpm full load the particle number concentration decreases at the increase of the ethanol percentage. This appears coherent with the sooting reduction tendency of oxygenated compounds. At 4000 rpm partial load, instead, a large increase of particle number is observed for E50 and E85 fuels because of a higher fuel impingement on the piston head and to the volatility properties of ethanol/gasoline blends. Ethanol addition, in fact, creates extremely favorable conditions for the formation of particles from the sooting compounds of gasoline. The results highlight that the improvement of engine design lead to a strong emissions reduction, but at the same time the fuel properties play an even more important role. For this matter is very important to better understand the effect of fuel composition on combustion process and then on soot formation and emissions.

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