EXPERIMENTAL ANALYSIS OF THE ETHANOL/GASOLINE BLENDS AND DUAL-FUEL PARTICULATE EMISSIONS IN A SMALL DISPLACEMENT SI ENGINE.

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Abstract
Over the recent years, great attention has been focused on ethanol as alternative fuel for both port fuel injection (PFI) and Direct Injection (DI) spark ignition (SI) engines. The higher octane number allows to operate with high compression ratio improving the engine efficiency, and the larger oxygen content contribute to reduce PM emissions. Ethanol can be both blended and dual fueled with gasoline. In this latter case, ethanol and gasoline are separately injected.
The aim of this study is to analyze the different methods of ethanol fueling in order to understand the configuration that better exploit the ethanol effect on the reduction of soot formation. To address this issue, the particle emissions from both the ethanol/gasoline blend, E30, and the ethanol/gasoline dual fuel, EDF, were evaluated. In this latter case, ethanol was direct injected and gasoline was injected in the intake duct. For both the operating configurations, the same percentage of ethanol was supplied: 30 %v/v ethanol.
The experimental activity was performed in a small displacement single cylinder engine and the tests were carried out at 3000, 4000 and 5000 rpm under full load condition. The particle emissions were measured downstream of a three way catalyst (TWC) by a smoke meter. Particle sizing and counting was performed in the size range from 5.6 nm to 560 nm by an Engine Exhaust Particle Sizer (EEPS).
For E30 the particle emissions are larger than for EDF because of the different contribution of gasoline. In EDF the better evaporation and mixing of gasoline, typical of PFI configuration, coupled with the soot reduction tendency of ethanol lead to low particle emissions.

Introduction
Spark ignition (SI) engines are moving towards the direct injection (DI) systems to improve fuel economy, engine efficiency and performance, however a larger amount of particle were emitted [1]. For this reason, the emission standard EURO6 regulates the number of particles emitted also for this engine [2]. One of the solutions for the reduction of particle could be the use of biofuels. This choice could be pursued allowing the environmental issues as well as the growing concerns on fossil fuels depletion.
According to the recent several studies [3,4, 5, 6] one of the most promising alternative fuel both for port fuel injection (PFI) and for Direct injection (DI) spark ignition (SI) engines is the ethanol [7,8]. In fact, it has a lot of beneficial qualities in terms of engine performance improvement and environmental impact such as higher octane number, latent heat of vaporization, faster laminar flame speed and larger oxygen content as compared to gasoline. A drawback of ethanol is the reduced energy density due to the lower heating value (LHV) which leads to a higher fuel consumption. Ethanol properties are listed in Table 1.

Table 1. Properties of the test fuel.

	Ethanol	Gasoline
H/C ratio	3	2.03
O/C ratio	0.5	0.01
Research Octane Number	106	91
LHV (MJ/Kg)	26.9	43-44
Latent heat of vaporization	840	305- 380

Typically ethanol is blended with gasoline, however interesting results were found out when it was dual fueled with gasoline [9].
The paper aims to analyze the different methods of ethanol fueling on particle emissions, in terms of mass and number concentration and size in order to understand the configuration that better exploit the ethanol effect on the reduction of particle emissions.

Experimental apparatus

Engine

The experimental activity was carried out on a 4-stroke single cylinder SI engine. Engine specifications are shown in Table 2.

Table 2. Engine specifications.

Cylinder volume [cm^3]	250
Bore [mm]	72
Stroke [mm]	60
Compression ratio	11.5
Max power [kW]	16 @ 8000 rpm
Max torque [Nm]	20 @ 5500 rpm

The engine was equipped with a prototype cylinder head of a naturally aspirated GDI engine. A prototype Magneti Marelli six-hole injector was located between the intake valves. The intake duct was equipped with a three-hole commercial low pressure injector, this configuration allowed PFI, DI and (dual fuel) DF operations. The spark plug was centrally located in the engine head.

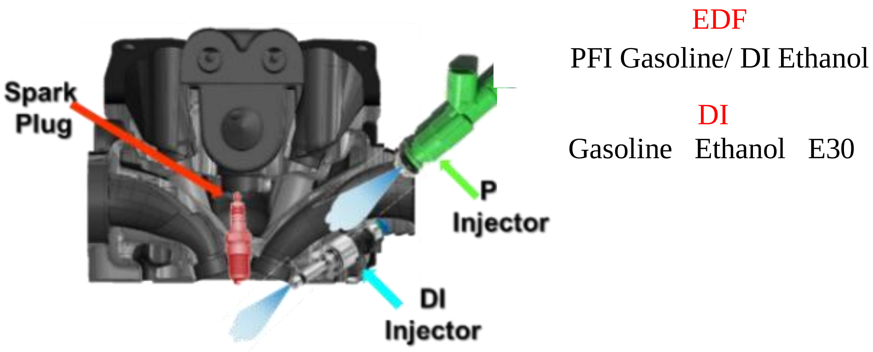

Figure 1. Scheme of the engine head and the investigated engine configurations.

The mass flow was measured by an oval gear meter operating in the range from 0.005 to 1.75 l/min. An electronic central unit allows the management of the injection and ignition timing. The engine was also provided with a three way catalyst (TWC) after- treatment device.

Methodology

The study was performed at three engine operating points: 3000, 4000 and 5000 rpm full load chosen as representative of typical urban driving conditions. Two injection systems were used both simultaneously and separately. In particular, the measurements were performed in DI and DF configurations.

For DI configuration, the engine was fueled with gasoline (GDI), Ethanol (EDI) and a blend of 30% v/v of ethanol in gasoline (E30), for DF configuration the gasoline was port fuel injected and the ethanol direct injected. It is worth noting that the investigation was performed with the same percentage of ethanol in EDF and E30: 70% v/v Gasoline- 30%v/v Ethanol.

The gasoline was injected in the intake duct at 3.5 bar and the EOI (end of injection) was fixed at 230 cad BTDC (crank angle before top dead center). The direct injected fuels, gasoline, ethanol and E30, were injected at 100 bar and the EOI was set at 315 cad BTDC. The EOI was chosen to have a good evaporation and mixing allowing a more homogeneous combustion [10].

The start of spark (SOS) was kept constant for each configurations and fuels and it was fixed at 22 cad BTDC at 3000 rpm and 24 cad BTDC at 4000 and 5000 rpm.

All the experiments were carried out at steady state conditions; the tests were repeated three times in order to consider engine repeatability.

Results and discussions

The particulate mass concentration is shown in Figure 2.

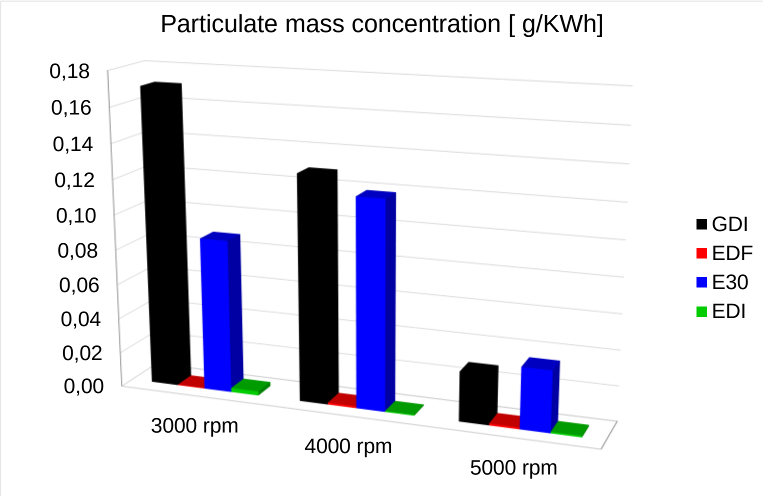

Figure 2. Particulate mass concentration for all the fuel and operating conditions.

For GDI configuration particle emissions are larger with respect to the other configurations. This is mainly due to the DI characteristics in terms of reduced time for the fuel evaporation and for air/fuel mixing. The fuel impingement on the cylinder wall and on the piston head also contributes to the soot formation. The beneficial effect of ethanol on particle emission reduction is evident for EDI [11]. In particular, the easier evaporation as well as the larger oxygen content, contribute to the lower particle formation and to a more efficient oxidation. For E30 the particulate emissions are larger with respect to EDI configuration but lower than GDI, due to the smaller amount of direct injected gasoline and to the ethanol properties. Low particle emissions were observed instead for EDF, in fact, in this configuration, the ethanol reduced tendency of soot formation is more evident [5,6].

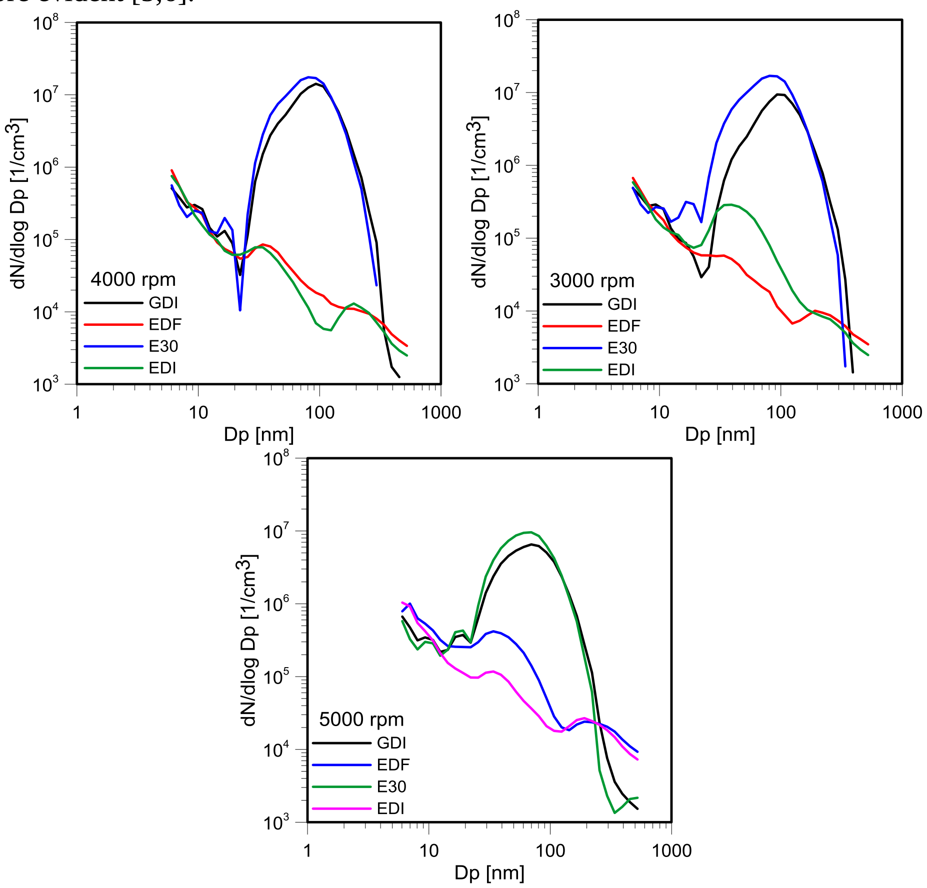

Figure 3. Particle size distribution functions for all the operating conditions.

Figure 3 displays the particle size distribution functions (PSDF) at all the engine speeds. It can be noted a strong accumulation mode for GDI and E30 was observed. On the other hand, EDF particle shows a size

distribution closer to that of EDI. Moreover, for GDI and E30 configurations a larger amount of particle was emitted with respect to the EDI and EDF configurations.
For a better understanding of the effect of the engine configuration on particle emissions it was also considered the number concentration and the mean particle diameter, depicted in Figure 4.
For E30 the number concentration of particles are about one order of magnitude larger with respect to the EDF. The different behavior of E30 respect to EDF is mainly due to the different contribution of gasoline on particle formation. In E30, the gasoline was direct injected, and its bad fuel evaporation and mixing and the large fuel impingement strongly contribute to particle formation. It is worth noting a large amount of particles emitted for E30 with respect to GDI. For E30 are emitted a lower amount of particles than GDI but their diameter are typically smaller. As for all the oxygenated fuels, also when ethanol is blended with gasoline, the particle emissions decreases in terms of mass but a large number of particles with smaller diameter are emitted. The oxygen content of ethanol, in fact, can affect the particle formation [11]. Nevertheless, only at 5000 rpm the particle diameter is larger than E30, resulting in a large particle mass as it reported in Figure 2. Moreover, it is interesting to highlight the large particle emissions at 3000 rpm for EDI with respect to EDF. The low temperature typical of this engine operating condition worsen the ethanol evaporation. For the EDF, instead, the combustion of gasoline-PFI increases the temperature and enhances the ethanol-DI evaporation at this engine point.

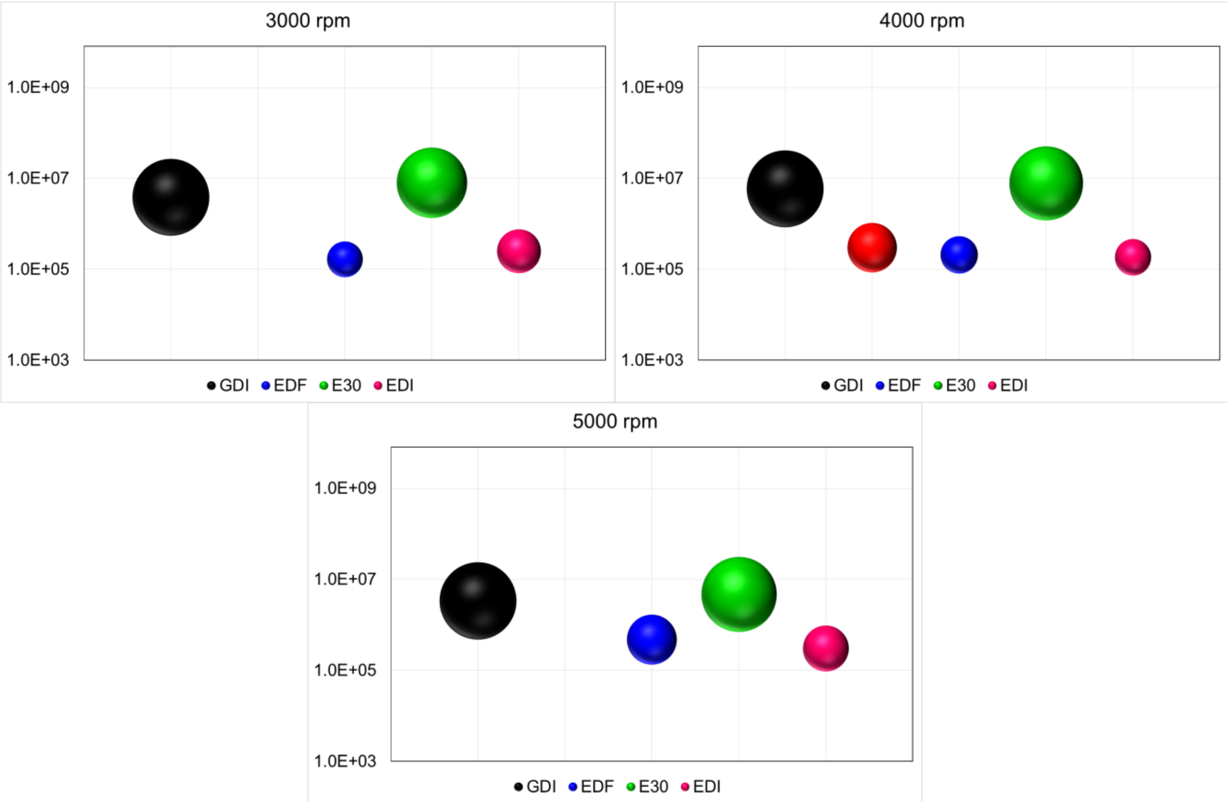

Figure 3. Particle number and mean diameter for all the tested conditions, the particle diameter is represented by the bubble size.

In the Figure 4 is depicted the different combustion evolution for E30 and EDF configurations. In E30, the wide diffusive flame highlights the presence of liquid fuels and rich zone due mainly to the gasoline not complete evaporation, and the large fuel impingement. In EDF, the gasoline has more time for evaporation and mixing as it was injected in the intake duct, as evidenced by the smaller diffusive flame.

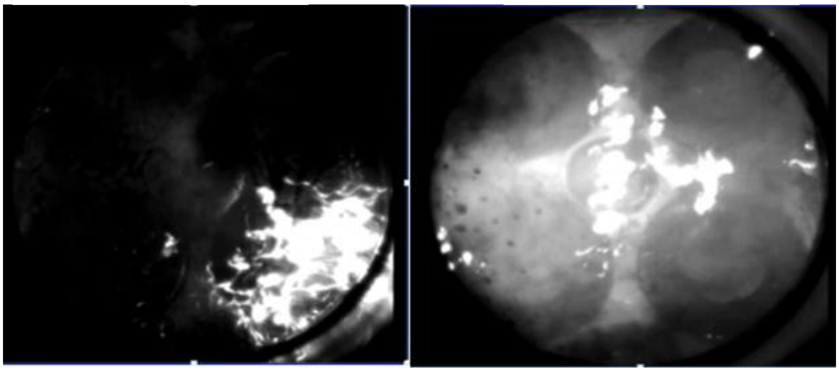

Figure 4. Combustion Evolution: E30 vs EDF at a typical crank angle

Conclusions

The particle emissions from ethanol/gasoline blend and dual fuel were characterized in order to assess the configuration that better exploit the ethanol properties such as the easier evaporation and the larger oxygen content that play a relevant role in the reduction of soot emissions.

The experimental analysis was carried out on a small displacement single cylinder engine. It was investigated typical urban driving conditions: 3000, 4000 and 5000 rpm under full load condition. The particle emissions were measured downstream of a three way catalyst (TWC) by a smoke meter and an Engine Exhaust Particle Sizer (EEPS) for the particle sizing and counting in the size range from 5.6 nm to 560 nm.

From the experimental results it can be observed that the ethanol has an overall positive effect on engine performance and particle emissions when it was dual fueled with gasoline. For E30, in fact, the impact of the direct injected gasoline results in large particle emissions similar at GDI configuration.

Definitions/Abbreviations

BTDC	Before top dead center
cad	Crank angle degree
DF	Dual Fuel
DI	Direct injection
DOI	Duration of injection
EDF	Ethanol dual fuel
GDI	Gasoline direct injection
LHV	Lower heating value
PFI	Port fuel injection
PSDF	Particle size distribution function
rpm	Revolution per minute
SOS	Start of spark
TWC	Three way catalyst

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