CORRELATION BETWEEN SOOT FORMATION AND EMISSIONS IN A SMALL DISPLACEMENT SPARK IGNITION ENGINE OPERATING WITH ETHANOL MIXED AND DUAL FUELED WITH GASOLINE.

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Abstract
This paper deals with the evaluation of the effect of different methods of ethanol fueling on in-cylinder soot formation and exhaust emissions in a small displacement spark ignition engine. The engine was fueled with gasoline and ethanol. In particular, the ethanol was both blended with gasoline (E30) and dual fueled (EDF). In this latter case, ethanol was direct injected and gasoline was injected into the intake duct. For both the injection configurations, the same percentage of ethanol was supplied: 30%v/v ethanol in gasoline. The experimental investigation was carried out in 4-stroke small single cylinder engine. The measurements were carried out at 2000 and 4000 rpm under full load condition. Optical technique based on 2D-digital imaging was used to follow the combustion process. Two-color pyrometry was applied to assess the soot formation. Particle emissions were measured at the exhaust by means of a smoke meter. Particle size distribution function was measured in the range from 5.6 to 560 nm by means of an Engine Exhaust Particle Sizer (EEPS). For E30 the in- cylinder soot formation and 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 a low particle formation and emissions.

Introduction
Although the majority of light-duty spark-ignition engines are equipped with port fuel injection (PFI) systems, most new production engines are increasingly fitted with DI (direct injection) systems [1]. The spark ignition direct injection (SIDI) engine can achieve higher fuel economy and power output. However, a relatively non-homogeneous air-fuel mixture formation in the combustion process of the SIDI engine leads to an increase of PN particle number emissions [2]. Several studies have demonstrated that the alternative fuels can reduce the particulate matter (PM) emissions. In particular, one of the most suitable fuel both for PFI and for SIDI engines is ethanol [3-5]. The higher octane number and the higher heat of

vaporization compared to gasoline, make ethanol the most attractive alternative fuel for SI engines. Moreover, the larger oxygen content results in particle emissions reduction. A drawback of ethanol is the reduced energy density due to the lower heating value (LHV) which leads to a higher fuel consumption. Frequently ethanol is added to gasoline, however interesting results where found out when it was dual fueled with gasoline [6]. The aim of this study is to investigate in-cylinder soot formation and exhaust emissions in a small displacement optical spark ignition engine fueled with different ethanol gasoline configurations. The experimental investigation was carried out in 4-stroke small single cylinder engine. The measurements were carried out at 2000 and 4000 rpm under full load condition. Optical technique based on 2D-digital imaging was used to follow the combustion process. Two-color pyrometry was applied to assess the soot formation. Particle emissions were measured at the exhaust by means of a smoke meter and an Engine Exhaust Particle Sizer (EEPS).

Experimental apparatus

Engine

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

Table 1. Engine specifications.

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

In Figure 1 is shown the scheme of the engine.

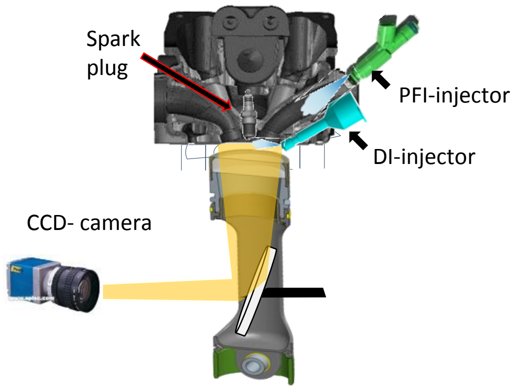

Figure 1. Scheme of the engine and the optical layout.

The engine head has four valves and a centrally located spark plug. The presence of two injectors allows the PFI, DI and DF operation. The engine is equipped with an elongated piston with a wide flat sapphire window in the head and a quartz ring replacing the upper side of the cylinder liner.

Methodology

The study was performed at two engine operating points: 2000 and 4000 rpm full load chosen as at typical urban operating conditions. PFI, DI and the dual fuel (DF) combustion modes were preformed. The engine was fueled with ethanol and gasoline. Pure gasoline was used in PFI and DI configuration as reference cases. The ethanol was supplied in DI configuration both pure and blended with gasoline, 30 %v/v ethanol in gasoline (E30). Moreover, ethanol dual fuel (EDF) configuration was performed injecting the ethanol directly in the combustion chamber and the gasoline into the intake duct. For both the injection configurations, the same percentage of ethanol was supplied. The fuels properties are listed in Table 2.

Table 2. Properties of the tested fuels.

	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

For all configurations, the start of Spark (SOS) was set to have the maximum brake torque (MBT) condition, and the end of injection (EOI) was chosen to have a good evaporation and mixing allowing a more homogeneous combustion. The injection pressure was set at 3.5 bar for PFI and 100 bar for DI. A CCD camera with sensitivity only in the visible range was used. Its spectral range spreads from 400 to 700 nm and it allows performing 2D flame visualization. In order to evaluate the spatial distribution of soot temperature and concentration the theory of two-color pyrometry was applied. A smoke meter (AVL 415S) was used for measuring the mass concentration. Particle number concentration and size were measured in the range from 5.6 to 560 nm by means of a TSI® engine exhaust particle sizer (EEPS). The exhaust was sampled and diluted by means of the Dekati® engine exhaust diluter (DEED), a PMP-compliant engine exhaust conditioning system. The dilution ratio was fixed at 1:79. A 1.5 m heated line was used for the sampling of the engine exhaust in order to avoid the condensation of the combustion water.

Results and discussions

To evaluate the effect of ethanol blending and dual fueling on particle formation, the combustion evolution was analyzed. In Figure 2 are represented the images of the combustion for the different engine investigated configurations at 2000 rpm at typical cad chosen as representative of the combustion process.

Figure 2. Combustion images for the tested fuels at 2000 rpm full load condition.

Localized diffusion flames characterize GPFI and EDF configurations whereas EDI, E30 and GDI are featured by widespread flames. In DI, the wide diffusive flame highlights the presence of liquid fuels and rich zone due mainly to the fuel not completely evaporated, the less time for air/fuel mixing, and the large fuel impingement. The effect of the ethanol is evident in EDI; the flame is less luminous and extended. In E30, the wider and more luminous flame with respect to EDI is due mainly to the presence of the gasoline. In EDF, instead, the gasoline has more time for evaporation and mixing as it was injected in the intake duct, as evidenced by the smaller diffusive flame. In order to study the effect of ethanol on soot formation and oxidation the in-cylinder soot volume fraction, f_v, was evaluated by applying the two color pyrometry theory. The integral in-cylinder soot concentration, f_v, for all the investigated conditions is shown in Figure 3.

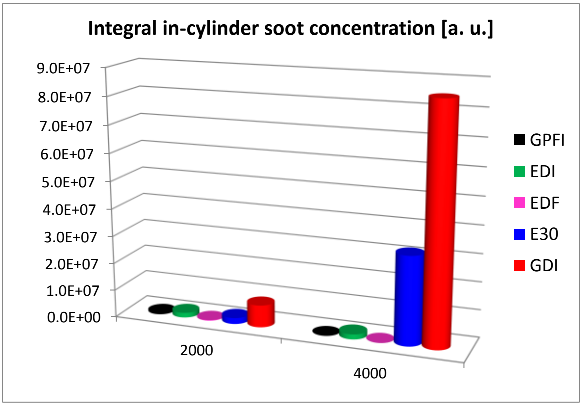

Figure 3. Integral in-cylinder soot concentration at 2000 and 4000 rpm.

It is interesting to highlight that at 2000 and 4000 rpm for DI configurations the f_v is higher than the other configurations. The beneficial effect of the ethanol on soot formation in DI configuration is more evident in EDI with respect to E30 due to the absence of gasoline. For EDF and GPFI configurations, the integral f_v is very low in all tested operating conditions, especially for EDF where the better evaporation and mixing typical of this engine configuration and the soot reduction tendency of ethanol, which was direct injected, results in low soot formation during the combustion process. Fig. 4 shows the particle concentrations measured at the exhaust in all tested engine operating conditions.

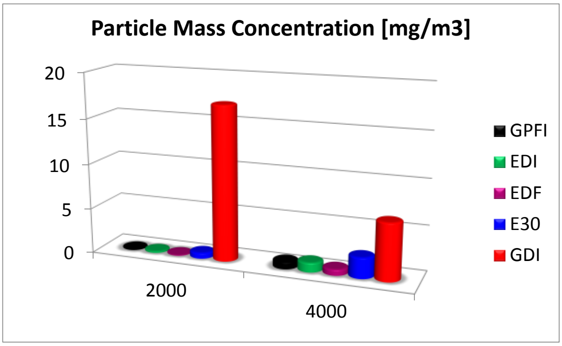

Figure 4. Particle mass concentration for all the tested conditions.

As expected, for GDI the particle emissions are larger with respect to the other engine configurations, mainly because of the different mixture formation process. The beneficial effect of ethanol is evident looking at the EDI results. A different behaviour is observed when the ethanol is blended or mixed with gasoline. In particular, for EDF the particle emissions are quite lower to that of EDI and GPFI. On the other hand, for E30 the particulate emissions are larger with respect to that of the other configurations, but lower than GDI. Fig. 5 depicts the particle number and mean diameters at all tested operating conditions. In particular, it was possible to consider two different ranges: particles smaller than 30 nm, full bar, and larger than 30 nm, striped bar.

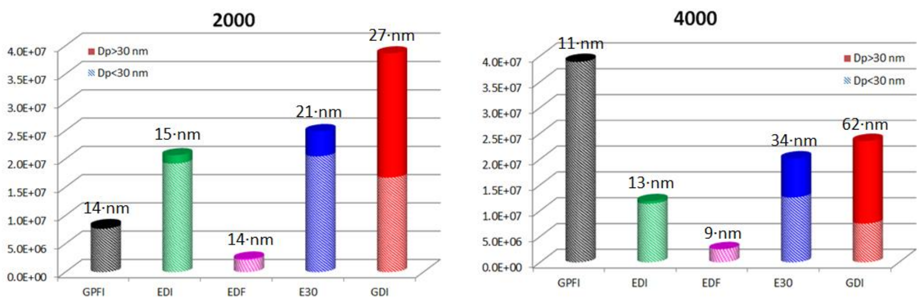

Figure 5. Particle number and mean diameter for all the tested engine configurations.

Particle number show a larger concentration of accumulation particles for GDI and E30 with respect to that of the other engine configurations. Nevertheless, for E30 the mean diameter is smaller than GDI resulting in lower particle mass, as shown in Figure 4. The ethanol reducing soot tendency is evidenced by the lower particle emissions for EDI especially at 4000 rpm. For EDF the particle emissions are lower than GPFI and the particles are slightly smaller. It is worth nothing the larger particles emissions for GPFI at 4000 rpm respect to 2000 rpm but with low diameter resulting in small particle concentrations with respect to the other engine configurations.
The larger particle formation and emissions for GDI and E30 is ascribable to the bad fuel evaporation and mixing. In the case of ethanol blends with gasoline, the particle emissions decrease in terms of mass and number because of the easier evaporation and the larger oxygen content of ethanol. The lower particle emissions for EDF with respect to EDI are due to improved evaporation of the ethanol ascribable to the combustion of gasoline-PFI. The difference between the EDF and the E30 is mainly due to the different contribution of gasoline on particle formation. In particular, in E30, the gasoline was direct injected in the combustion chamber resulting in a large fuel impingement and a worsen fuel evaporation and mixing. In EDF configuration, the gasoline was injected in the intake port: the better evaporation and mixing typical of this engine configuration coupled with the soot reduction tendency of ethanol. Moreover, it results in low particle emissions with small mean diameters.

Conclusions

The objective of this study was to analyze the correlation between soot formation and emissions in a small optical displacement single cylinder engine with ethanol dual fueled and blended with gasoline. It was investigated typical urban driving conditions: 2000 and 4000 rpm under full load condition. The particle emissions were measured at the exhaust 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. The particle formation and 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 formation and emissions. The beneficial effect of ethanol is better exploited when it was dual fueled with gasoline. These results can be mainly ascribed to the fuel properties and to the injection configuration. For E30, in fact, the impact of the direct injected gasoline results in large particle emissions similar to that of the GDI configuration. From this analysis can be argued that the dual-fuel injection system allows to better underline the better ethanol properties, such as the easier evaporation and the larger oxygen content as well as the cooling effect, which paly a relevant role both in the improvement of the engine performance and particle emission reduction.

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Acknowledgments

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Definitions/Abbreviations

cad	Crank Angle Degree
DF	Dual Fuel
DI	Direct Injection
EDF	Ethanol Dual Fuel
GDI	Gasoline Direct Injection
PFI	Port Fuel Injection
rpm	Revolution Per Minute
EDI	Ethanol Direct Injection
E30	Blend of 30% ethanol – 70% gasoline

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