EFFECT OF THE FUEL INJECTION SPLITTING ON THE COMBUSTION PROCESS IN A PFI BOOSTED SPARK-IGNITION ENGINE

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Abstract

Future stringent legislation on emissions in combination with the market request of an increase in engine efficiency and optimization poses a great challenge to the engine and components manufacturers. The technologies developed in the last years for Spark Ignition (SI) engines such as turbocharging and variable valve actuation are not able to totally satisfy the future normative. More progress still has to be made in terms of in-cylinder combustion process and efficiency.

The aim of this paper is the optimisation of a boosted SI engine in terms of performances, fuel consumption and pollutants emissions with low costs. The experimental activity was carried out on a port fuel injection SI optical engine, equipped with a commercial four-valve head. Innovative injection strategies were tested: in particular, single and double injections were performed when the intake valves were open.

Optical techniques based on 2D-digital imaging were used to follow the fuel injection in the intake manifold and simultaneously the flame propagation in the combustion chamber. Conventional measurements of engine parameters and exhaust emissions completed the experimental investigations.

The tests demonstrated that the double injection strategies were characterized by higher combustion process efficiency than single injection on. The injection splitting resulted a suitable solution for the reduction in pollutants concentration in the combustion chamber and at the exhaust with a good compromise between performance and fuel consumption.

Keywords: *PFI SI engine; boosting; double injection strategies; fuel deposits; optical diagnostics*

1. Introduction

Recent studies have evaluated that more than 220 million in-use passenger cars are in enlarged Europe (EU-23) and the increasing annual trend is around 2.5-3% [1]. More than 98% of these cars are powered by internal combustion engines fuelled with gasoline and diesel oil. Thus, the development of a sustainable transport requires the optimization of these engines in terms of fuel consumption, pollutants emission without giving up performance, durability and reliability at an affordable price. With respect to the gasoline-fuelled vehicles, the downsizing has allowed the increase in engine power and torque without the increase in cylinder capacity and the reduction in pumping losses and gases-to-wall heat transfer. The turbocharging has kept the same specific output performance by an increase in air and fuel content of the combustion chambers. Finally, the variable valve actuation has allowed to provide more enthalpy to the turbine and thus to obtain faster turbocharger acceleration [2, 3].

Nevertheless all these technologies don't satisfy totally the future normative. More progress still has to be made in terms of in-cylinder combustion process and efficiency.

In this work, a low-cost solution is proposed to optimize the boosted PFI SI engines. In order to reduce the fuel consumption and the pollutants emissions maintaining the engine performances, the splitting of the fuel injection in the intake manifold was tested. Single and double injection strategies were performed in the open-valve condition. The experiments were realised in a partially transparent single-cylinder PFI SI engine with an external boosting device. In-cylinder optical investigations were correlated with the engine parameters and with the exhaust emissions measured by conventional methods.

2. Experimental apparatus

Transparent Engine

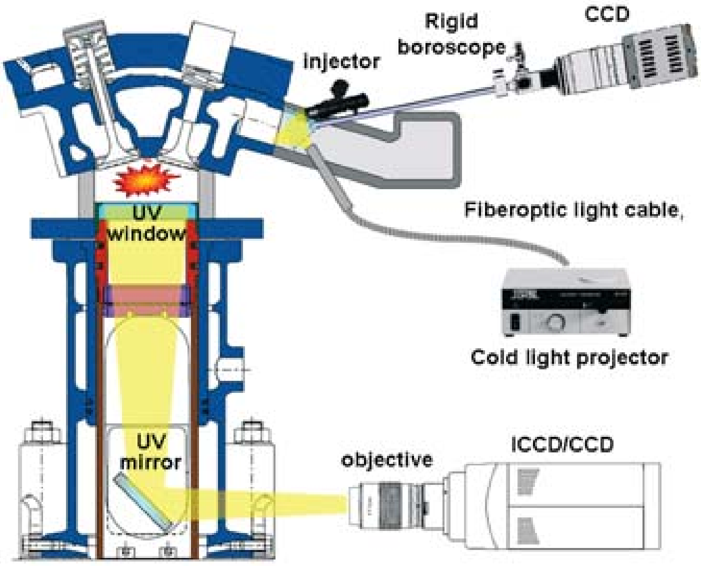


Fig. 1. Sketch of the experimental apparatus the optical investigations

An optically accessible single cylinder ported fuel injection (PFI) spark ignition (SI) engine was used for the experiments. It had a displacement of 399 cm3 and it was equipped with the cylinder head of a new generation of SI turbocharged engine. The head had four valves and a centrally located spark plug. A quartz pressure transducer was flush-installed in the region between intake-exhaust valves [4].

The combustion pressure measurements were performed for all the selected operating conditions. The in-cylinder pressure was evaluated on an individual cycle basis and/or averaged on 400 consecutive cycles [5].

An external device controlled the intake air pressure in a range of 1000-2000 mbar and the temperature in a range of 290-340 K. The engine piston was flat and transparent through a quartz window (ϕ = 57 mm). To reduce the window contamination by lubricating oil, an elongated piston arrangement was used together with unlubricated Teflon-bronze composite piston rings.

Fig. 1 shows the experimental apparatus for the optical investigations. During the injection in the intake manifold, a fiber optic cable coupled with a flash light projector illuminated the fuel jet. The lowest flash duration was 30 μs and the maximum energy of flash was 16 J. The jet visualization was performed through a rigid borescope with a rod lens telescope matched with a color CCD camera. The CCD had an array size of 640 x 480 pixels and 12-bit dynamic range digitization. The maximum recording rate was 15 Hz with the shortest shutter time of 10 μs.

During the combustion process, the light passed through a UV-fused silica window located in the piston and it was reflected towards the optical detection assembly by a 45° inclined UV-visible mirror located in bottom of the engine. Then the light was focused by a 78 mm focal length, f/3.8 UV Nikon objective on an intensified cooled CCD camera (ICCD). The ICCD had an array size of 512 x 512 pixels and 16-bit dynamic range digitization at 100 kHz. The ICCD spectral range spread from UV (180 nm) until visible (700 nm).

Finally the soot flame imaging was detected by the same 12-bit digital CCD colour camera used for the fuel jet visualization. The CCD was coupled with a 50 mm focal length, f/3.8 Nikon lens. This optical assessment allowed a spatial resolution of 100 μm/pixel. The spectral range of the camera was 290-800 nm. The spatial distribution of soot temperature and concentration was obtained by the two colour method. More details about this methodology are reported in [6].

For all the optical measurements, the synchronization between the cameras and the engine was made by the crank angle encoder signal through an Engine Timing Unit (ETU). The exposure time of the cameras was fixed at 41.6 μs. It corresponds to 0.5° crank angle (CA) at engine speed of 2000 rpm. Both cameras were not cycle resolved detectors. In this work, each image was detected at a fixed crank angle of different engine cycles. The dwell time between two consecutive images was set at 41.6 μs.

AVL Indimodul recorded the TTL signal of CCD and ICCD acquisition together with the pressure trace from the pressure transducer. In this way, it was possible to determine the crank angles where optical data were detected.

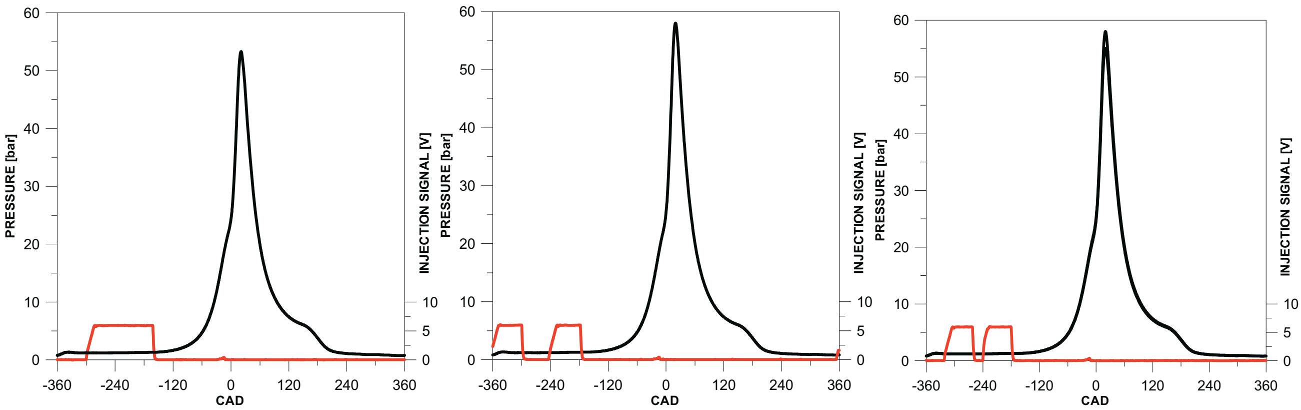
Steady-state measurements of CO, CO2 and HC were performed in the raw exhaust by Non-Dispersive Infrared Detectors (NDIR). An opacimeter was employed to measure particulate mass (PM) concentration [7]. A lambda sensor was placed at the engine exhaust to measure the equivalence ratio.

3. Results and discussion

All the tests presented in this paper were carried out at engine speed of 2000 rpm and at Wide Open Throttle (WOT). The absolute intake air pressure and the temperature were fixed at 1400 mbar and 323 K, respectively. Commercial gasoline with octane number 95 was used.

Tab. 1. Engine operating conditions, performances and CO emission

Test label	number of inj.	Duration of Inj. [CAD]	Start of Inj. ATDC [CAD]	IMEP [bar]	COV_{IMEP} [%]	CO [g/kWh]
OV1-300	1	138	-300	13.4	2.0	43.3
OV2-360	2	65 65	-360 -240	13.8	1.3	40.4
OV2-320	2	60 60	-320 -240	13.3	1.2	32.6



OV1-300 **OV2-360** **OV2-320**

Fig. 2. Injection signal and pressure traces averaged on 400 consecutive cycles for the selected operating conditions

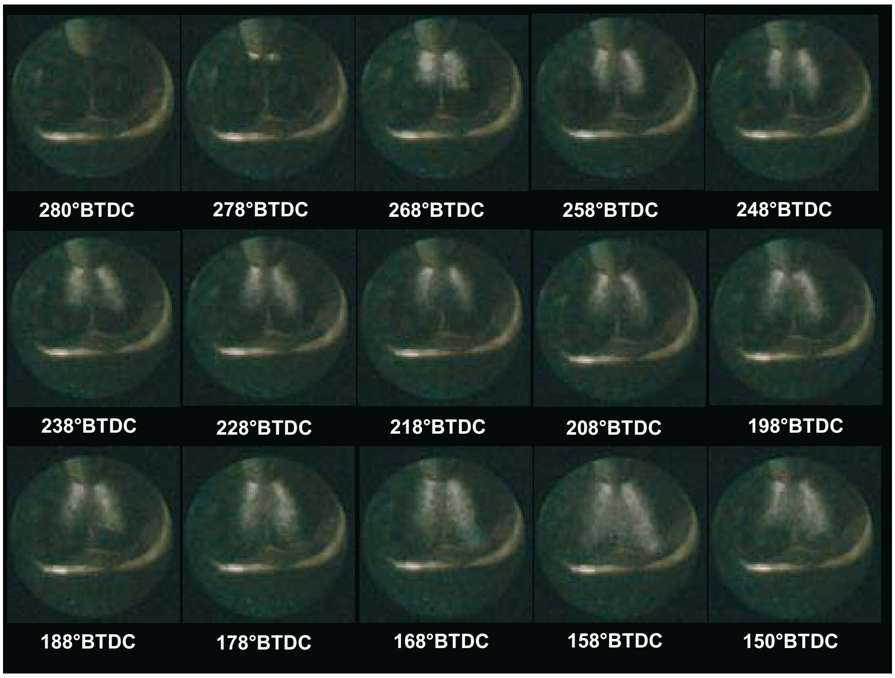
For all the tests, the injection-duration was chosen to obtain a stoichiometric equivalence ratio. The spark timing was fixed to operate in the Maximum Brake Torque (MBT) condition [8]. Different fuel injection strategies were tested. An open-valve (OV1-300) and two double fuel injection strategies were analysed. The OV2-360 had the highest dwell time between the two injections to operate in open-valve condition. The OV2-320 condition was characterised by the minimum dwell time allowed by the mechanical inertia of the injector. More details about the engine operating conditions are reported in Tab. 1.

Fig. 2 reports the averaged pressure traces for the selected fuel injection strategies. Even if the cycle-to-cycle variation and the heat transfer between the different components of the optical engine induced a thermal evolution and fluctuation of the maximum pressure signal, the IMEP and COV resulted good and comparable with those measured for real multi-cylinder engine [2]. Moreover, these data show an improvement in terms of stability from the single injection strategy to the double ones. This result matches with the decrease in CO emission reported in Table 1. In fact, the level of CO emission in the exhaust of an IC engine varies with the fuel-air ratio. For fuel-rich mixtures, high CO concentrations in the exhaust emissions are generally observed [9]. Since in these experiments the engine operated at stoichiometric fuel-air ratio, the CO emission in the exhaust was due to the presence of locally rich zones in the chamber. Thus, it is possible to state that in the OV2-360 condition a more complete combustion took place if compared to the other single injection strategies.

Unfortunately, the pressure measurements and the exhaust characterisation give only overall information and they are not sufficient to follow the whole process in details. To this aim, the optical techniques are suitable to give details on thermo and fluid dynamic phenomena that occur from the injection in the intake manifold until the exhaust ports opening. In Fig. 3 it is reported the fuel injection visualization in the intake manifold for OV1-300 and OV2-360, respectively. For both conditions, the fuel droplets partially impinge on the intake manifold walls and on the valves steams. This can induce the formation of fuel film deposits. The splitting of the fuel injection improves the fuel-air mixing by means of the dwell time between the injections; the more gradual injection in the OV2-360 allows obtaining a more complete liquid vaporization. This affects the fuel film formation in the intake manifold and the fuel distribution in the combustion chamber. Thus in the double injection conditions, a more homogeneous mixture is obtained.

With respect to the combustion process, the first evidence of the flame was detectable at 2 CAD after the spark timing (ASOS). Then, the flame front spread with radial-like behaviour for about 16 CAD. This result agrees with those obtained in previous optical investigations in comparable operating conditions [10, 11].

The Fig. 4 reports the digital images that represent the flame propagation for all the selected fuel injection strategies.



OV1-300

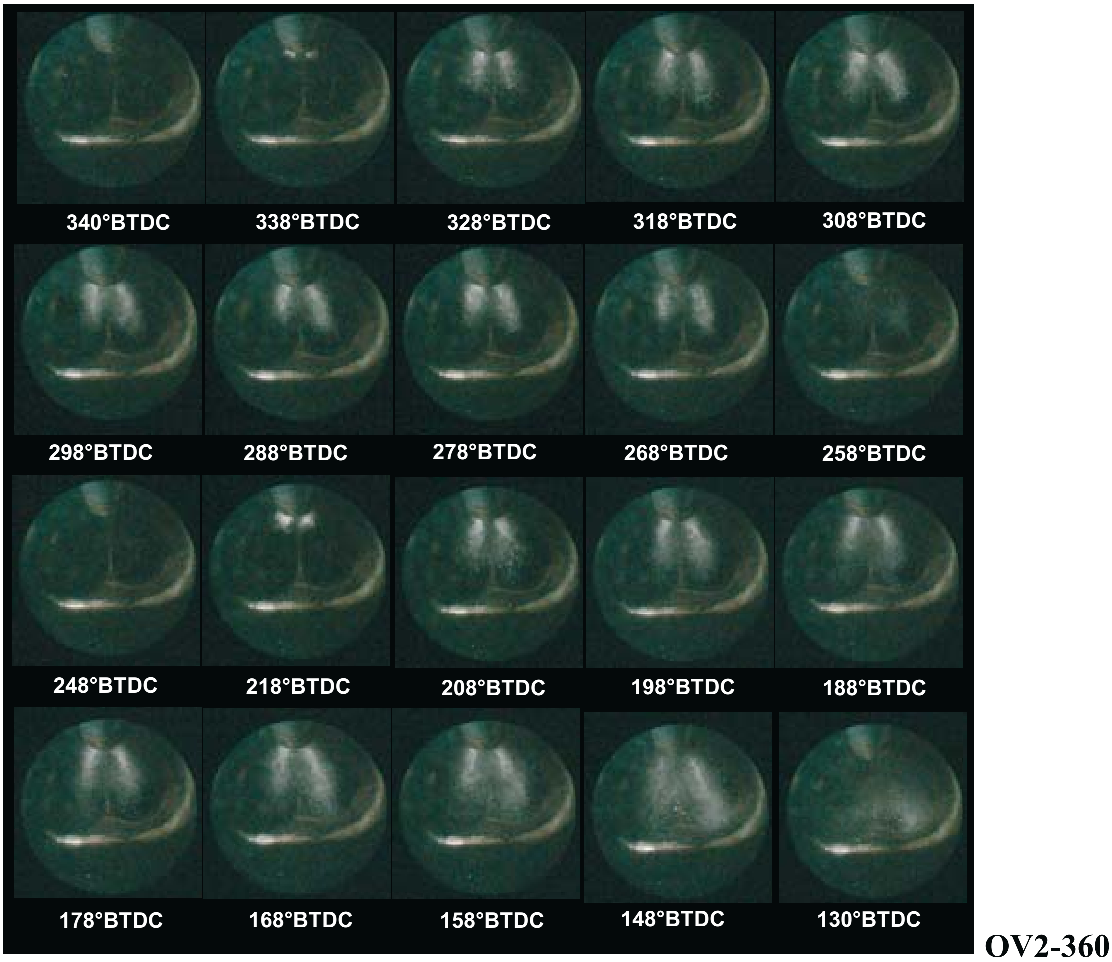


Fig. 3. Fuel injection detected in the intake manifold for the conditions OV1-300 and OV2-360

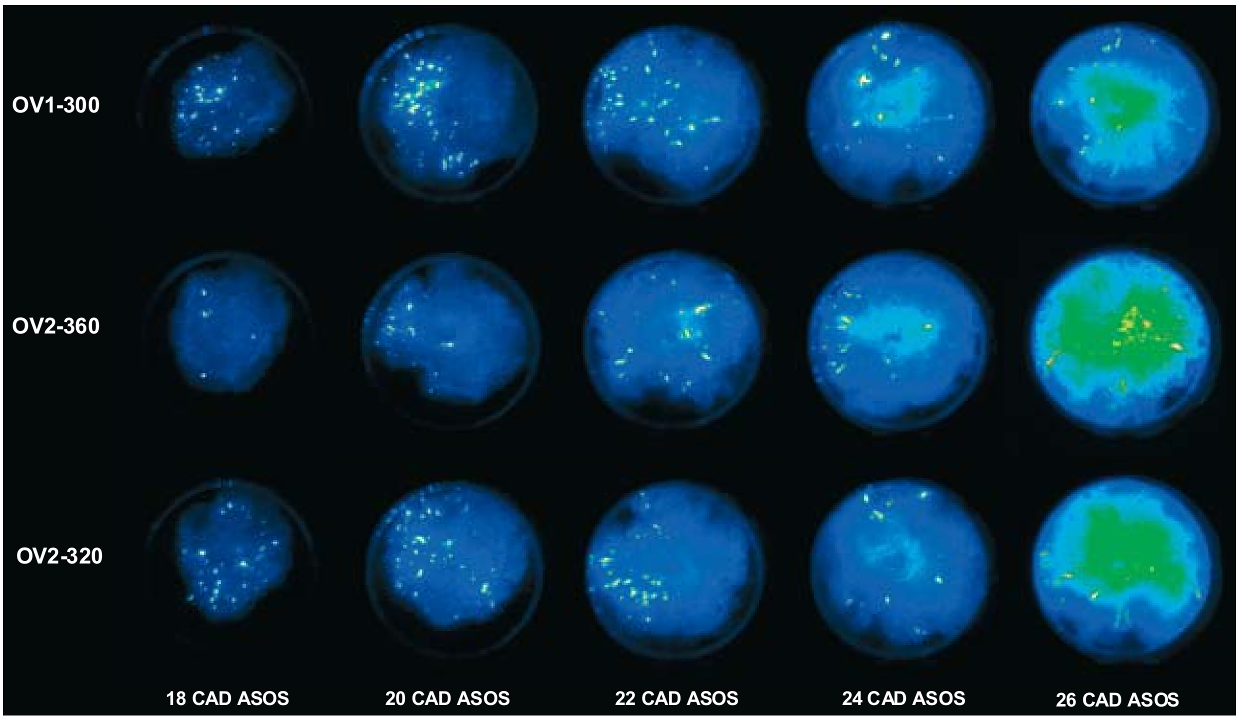


Fig. 4. UV-visible flame emission detected in the combustion chamber for the selected operating conditions

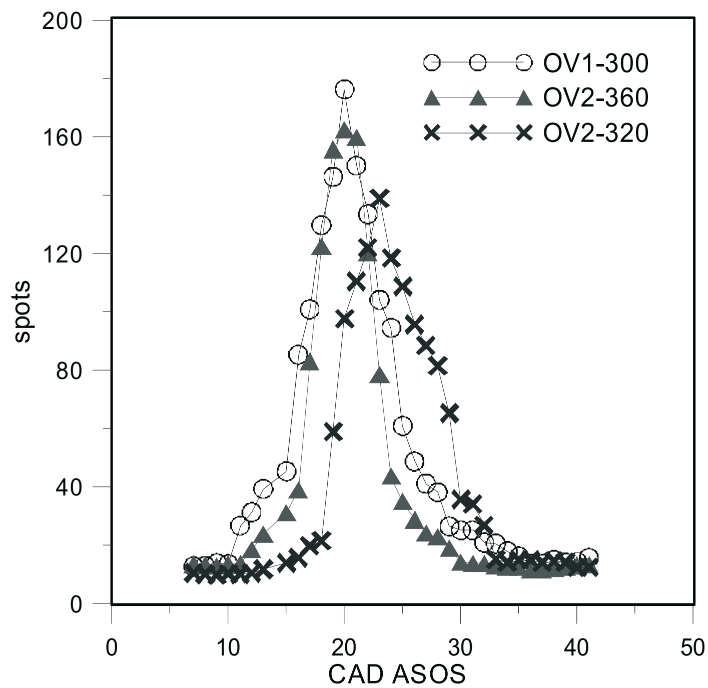


Fig. 5. Number of the bright spots detected in the combustion chamber for the selected operating conditions

In every condition, some asymmetries in the flame front shape were observed from 18 CAD ASOS. The region between the intake valves seemed to be off-limit for the flame. This effect was due to fuel film deposits on the intake ports caused by the fuel impingement on the valves steams in the intake manifold [12]. Once formed, the fuel film developed dynamically under the influence of gas flow [13]. Heat exchange between intake ports and the surrounding gas led to the fuel evaporation. This effect influenced the composition of the mixture and hence the combustion process. In particular, liquid fuel vaporization could reduce the flame speed and the complete flame propagation creating locally rich-zones.

In the selected operating conditions, the most of the injected fuel droplets were carried by the gas flow into the combustion chamber. A little part of these stuck on the cylinder walls and a part was deposited on the piston surface. These fuel deposits created locally fuel-rich zones with millimetre size. When the flame approached these zones, several small ignition surfaces appeared as bright spots as shown in Fig. 4, this was also observed in [4, 14].

A retrieving procedure of the UV-visible flame emission data was realized to evaluate the area and number of the bright spots. In particular, each colour image was converted in 2-bit image fixing a threshold of 70% for the pixel luminosity. In this way, the normal flame front luminosity was removed and the bright spots enhanced. Then the evaluation of the number and pixel size of the bright spots was obtained.

As shown in Fig. 5, a well-atomised fuel injection improved the homogeneity of air-fuel ratio distribution in the combustion chamber and the number of bright spots was lower in the double injection OV2-360 than the single injection OV1-300.

To better understand the effect of the fuel injection splitting on the combustion process, 2D digital imaging of flame was performed in the late combustion phase. A selection of images is reported in Fig. 6.

When the flame front interacted with the fuel deposits on the cylinder walls, the diffusion-controlled flames were observed as also reported in [10, 14]. For both double injection strategies the luminosity and spatial distribution of these flames was lower than the single injection one. Moreover, the residual luminosity at the exhaust valves opening (around 170 CAD ASOS) was strongly reduced.

As reported in previous spectroscopic investigations [14], the diffusion controlled flames were characterized by a strong continuous spectrum that increased with the wavelength from the visible range to the IR. This indicated the presence of soot [15]. To study the effect of the different operating conditions on the soot concentration, the two-colour pyrometry was applied [6, 15].

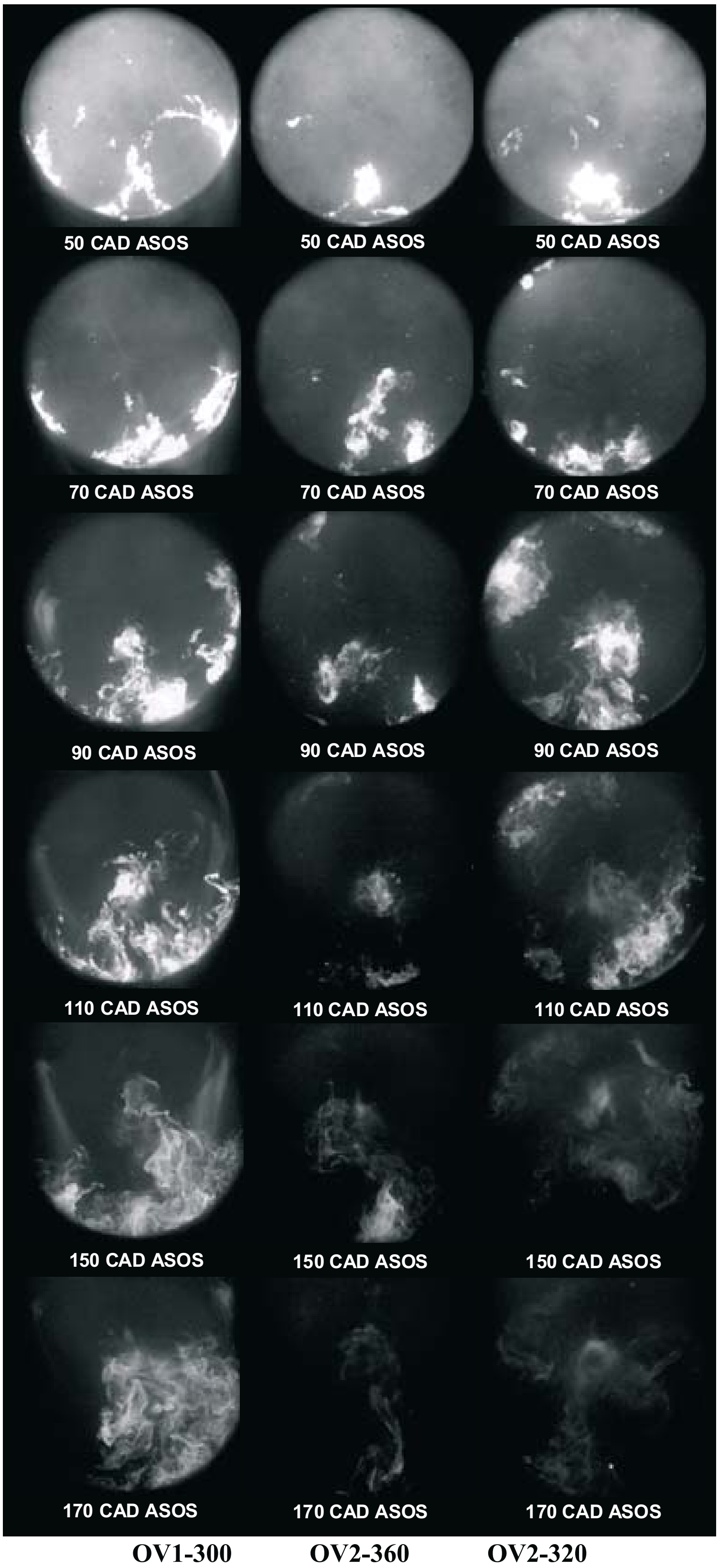


Fig. 6. Flame emission detected in the late combustion phase

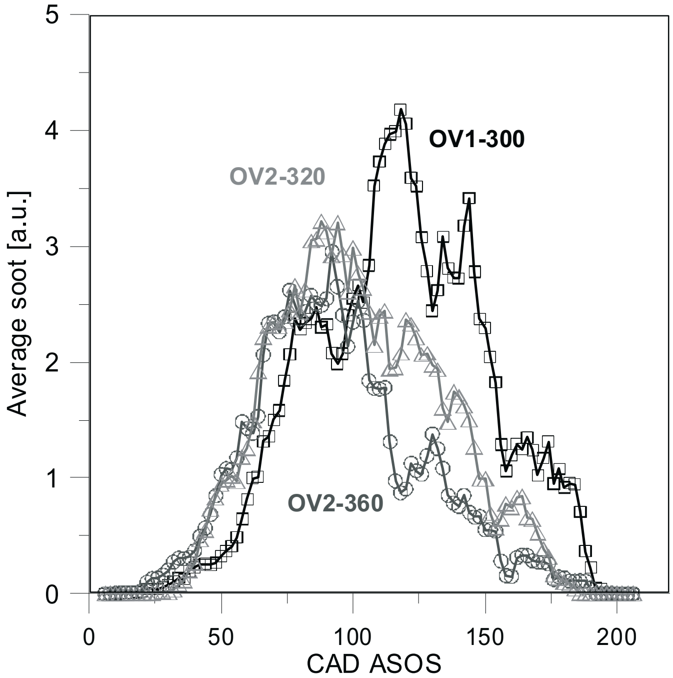


Fig. 7. Average soot concentration measured in the combustion chamber

	HC [%]	PM [%]	CO_2 [%]	BSFC [%]
OV2-360	12.6	69.2	0.3	1.1
OV2-320	6.0	67.9	0.8	1.3

Tab. 2. Exhaust pollutant emission and specific fuel consumption evaluated as percentage reduction for the double injection condition with respect to the single injection one

Fig. 7 reports the time evolution of the soot concentration averaged on the combustion chamber volume. It can be noted that the highest concentration and the total soot amount in the combustion chamber was lower for both double injection strategies. This can be due to the better fuel-air interaction in the intake manifold. Moreover it is a little bit smaller in the OV2-320 than in the OV2-360 indicating the effect of the lower dwell time between the two injections.

If compared with the single injection strategy, the double injections showed higher combustion efficiency with a direct effect on the exhaust emission, as reported Tab. 2.

This was confirmed by the little reduction in the CO_2 concentration and BSFC. On the other hand, a strong decrease in the particulate matter and HC concentration was observed.

In conclusion, the splitting of the fuel injection allowed the reduction in pollutants concentration and fuel consumption without influence on the performance.

4. Conclusions

Fuel injection strategies based on the injection splitting were tested in a boosted PFI SI engine.

All the measurements were realised in a partially transparent single-cylinder engine, equipped with a four-valve head and an external boosting device. The engine worked at WOT and stoichiometric equivalent ratio.

Optical techniques based on 2D-digital imaging were used to follow the fuel injection in the intake manifold and flame propagation in the combustion chamber. Moreover, two-colour pyrometry was employed to measure the soot concentration in the combustion chamber. The optical investigations were correlated with the engine parameters and exhaust emissions.

The experiments demonstrated that the double injection strategies were characterized by higher combustion process efficiency than single one. They provided a strong reduction in particulate matter in the combustion chamber and at the engine exhaust and a good decrease in the specific fuel consumption. The splitting of the fuel injection showed a good potentiality to optimize the boosted PFI SI engines.

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