

Water Injection: a Technology to Improve Performance and Emissions of Downsized Turbocharged Spark Ignited Engines

Cinzia Tornatore, Daniela Siano, Luca Marchitto, Arturo Iacobacci, and Gerardo Valentino
Istituto Motori CNR

Fabio Bozza
Univ of Naples - Istituto Motori CNR

ABSTRACT

Knock occurrence and fuel enrichment, which is required at high engine speed and load to limit the turbine inlet temperature, are the major obstacles to further increase performance and efficiency of down-sized turbocharged spark ignited engines. A technique that has the potential to overcome these restrictions is based on the injection of a precise amount of water within the mixture charge that can allow to achieve important benefits on knock mitigation, engine efficiency, gaseous and noise emissions.

One of the main objectives of this investigation is to demonstrate that water injection (WI) could be a reliable solution to advance the spark timing and make the engine run at leaner mixture ratios with strong benefits on knock tendency and important improvement on fuel efficiency. Experiments were carried out on a downsized port fuel injection (PFI) twin-cylinder turbocharged spark ignition engine equipped with a variable valve actuation (VVA) system over the speed range from 2500 to 4500rpm (step of 500 rpm) under a medium-high load condition. The engine was equipped with a prototype low-pressure injection system including two solenoid injectors installed in the runners, upstream of the gasoline ones, able to inject, at phased timing, a controlled amount of water within the intake ports.

Experiments were carried out at wide open throttle (WOT) conditions choosing a water to gasoline mass ratio of 0.2, as a result of a previous investigation carried out to optimize the water amount in terms of engine performance. At the different engine speeds and at full gasoline operations, the relative air-fuel ratio (λ - measured by a lambda meter located in the exhaust, upstream of the three-way catalyst) was that set by the standard electronic control unit (ECU) map corresponding to the knock limited spark advance. As the WI was activated the amount of fuel was steadily reduced up to reach the stoichiometric condition and a sweep was performed up to the most advanced spark timing without knock occurrence.

In-cylinder pressure data, acquired by pressure sensors flush-mounted within the combustion chamber of both cylinders, allowed estimating the main combustion parameters such as the rate of heat release and the combustion phasing. The effect of water injection on turbine inlet temperature and combustion efficiency, estimated from the exhaust gaseous emissions (HC, CO, CO₂), are also presented. Further, combustion noise analysis carried out post-processing the in-cylinder pressure signal, decomposed into three sub-signals corresponding to the relevant physical phenomena: pseudo-motored operation (compression-expansion), combustion, and combustion chamber resonance. Such pressure signal decomposition was applied to find cause-effect relationships between the source signal generated by the engine during combustion process and both the objective and subjective parameters of the noise. The results coming from such analysis are discussed to determine the capability of water injection to reduce combustion noise level and improve sound quality index.

CITATION: Tornatore, C., Siano, D., Marchitto, L., Iacobacci, A. et al., "Water Injection: a Technology to Improve Performance and Emissions of Downsized Turbocharged Spark Ignited Engines," *SAE Int. J. Engines* 10(5):2017, doi:10.4271/2017-24-0062.

INTRODUCTION

The automotive industry, during the last decade, has strengthened a tendency in producing low-displacement spark ignition engines. To this end, engine boosting, provided by a turbocharger, is also required to meet the same (or greater) levels of performance. In [1], the authors point out that turbocharged engine market share increased from 3% in 2010, up to 18% in 2015 with a perspective of 30% through 2020. Based on the above trend, it is estimated that by 2019-2020, 3-cylinder

engines will get a market share about twice the level of 2015, while 6-to 8-cylinder engines will considerably decrease their overall fraction. Engine downsizing and turbocharging in fact, indirectly reduces fuel consumption [2-3] since, at a constant vehicle demand, a smaller displacement engine operates at higher loads, resulting in lower throttling losses under normal driving conditions, and in some reduction of heat transfer losses. In addition, smaller engines typically have lower friction losses due to smaller bearings and cylinders.

The above well-known advantages of the downsizing architecture are limited by the boost-induced knock or even pre-ignition onset at high loads [4, 5, 6]. Knock occurrence can be easily prevented by reducing the spark advance [5]. However, this strategy penalizes the thermodynamic efficiency [5], and involves increased exhaust gas Temperatures at the Turbine Inlet (TIT). For this reason, a reduced spark advance is often coupled to a strong enrichment of the intake mixture, with further fuel consumption penalties [6]. Knock mitigation hence represents one major prerequisite to attain a better fuel economy at high loads.

Among the available techniques to reduce the knock tendency - such as: enhanced turbulence levels and reduced intake air temperature [7,8], employment of high octane number fuels [8, 9, 10, 11], adoption of cooled Exhaust Gas Recirculation (EGR) [12, 13, 14, 15], the injection of liquid water, either within the cylinder or at the intake ports [16, 17, 18, 19], is gaining an increased interest. This solution can be applied with minor architecture modifications, and employing components of well-assessed technology, such as high- or low-pressure solenoid injectors. The potential benefits to obtain a reduction of the charge temperature [16] is related to the latent heat of vaporization that for the water is 2250kJ/kg, much higher than that of gasoline (~300kJ/kg) that changes according to the hydrocarbon blend of the gasoline. The above effect is enhanced by the increased heat capacity of the charge, due to the higher content of inert gases in the combustion chamber.

In the current literature, some papers have already shown, from an experimental point of view, the potential of the water injection (WI) in terms of knock mitigation at high loads. Soyelmez et al. [17] studied its effects on the performance of a naturally aspirated 4-cylinder LPG SI engine. WI allowed to always set the spark timing at the maximum brake torque (MBT) value, determining increased engine torque and power, depending on the adopted Water-to Fuel mass ratio (W/F). Maximum benefits were obtained at the highest investigated W/F ratio, equal to 0.5. The results also showed that the Brake Specific Fuel Consumption (BSFC) and the exhaust gas temperature decreased as the W/F ratio increased. Similar outcomes were obtained by Kim et al. [18], who investigated the effects of direct in-cylinder water injection. Tests were performed in the range of engine speed of 1500-3000 rpm achieving an improvement in BSFC and a reduction of the exhaust gas temperature, as a consequence of advanced spark timing without knock occurrence. Busuttill and Farrugia [19] addressed the potential of water injection in a prototype single cylinder engine equipped with a port fuel injection and a low-pressure water injection. The published results showed maximum torque improvement of 16 %, with a fuel-to-water ratio of 4.65 by volume. In [16], Hoppe et al. investigated a direct injection single-cylinder research engine equipped with a direct water-injector. The combustion water was recycled from the exhaust gas, cooled down to its dew point, and then directly injected within the cylinder. An efficiency increase of 3.3% - 3.8% was found in the region of the minimum BSFC, through a combination of water injection, Miller cycle and cooled external EGR. More significant efficiency improvements, around 16%, were obtained at low speed and high load, mainly related to a combustion phasing optimization. Iacobacci et al. [20] explored the effects of water injection on performance and emissions in a PFI twin-cylinder turbocharged spark ignition engine in the interval of engine speed

from 3500 to 4500rpm, at high engine load. The results showed that, at 20% water mass fraction, an increase of IMEP up to 7.3% was achieved with respect to the reference gasoline case, due to better combustion phasing associated with advanced spark timing without knock occurrence. The increase in the heat capacity of the in-cylinder charge also allowed to reduce significantly the inlet turbine gas temperature up to 50°C.

Water injection was also investigated from a numerical point of view [21, 22, 23]. In [21], Berni et al. utilized a detailed 3D-CFD mode, to show the potential of port injected methanol-water mixture in a turbocharged DISI engine at the peak power operating conditions (7000rpm). They analyzed different fractions of methanol and water with the objective to replace the fuel enrichment. They found that, because of the lower chemical reactivity and the faster burn rate given by the methanol, advanced spark timings were allowed with relevant reduction of the fuel consumption. Boretta [22] analyzed by a 1D model the effects of WI for a turbocharged SI engine fueled with pure ethanol. Numerical findings showed that the port injection of liquid water involved the possibility to apply higher compression ratios, boost levels, and spark advances closer to the MBT.

De Bellis et al. in [23] performed a numerical calibration of a water-injected engine under knock limited operation, highlighting how a limited amount of injected water, up to about 0.17 water-to-fuel ratio, allowed completely suppressing knock occurrence and mixture over-fuelling at high load. A further increase of the W/F ratio would also allow to operate the engine at MBT, while inducing, however, excessive in-cylinder peak pressures, which may affect the mechanical safety.

With reference to the above discussed literature overview, in this paper, a more detailed experimental analysis of the water injection technology is presented with the aim to quantify its impact on main engine performance parameters, such as fuel consumption and IMEP, and control parameters (knock-limited spark advance, A/F ratio and TIT). Further, combustion process is deeply investigated in terms of heat release rate, efficiency, noxious species emissions, and combustion induced noise. Finally, some considerations on the impact of WI on cyclic variability and combustion noise are also discussed.

Preliminarily, the experimental setup and the considered operating conditions are illustrated. Then, the WI impact on different performance and control parameters is discussed, highlighting pros and cons of the WI technique. The extended experimental dataset will also serve for a 1D model validation, presented in a companion paper.

EXPERIMENTAL SETUP

Engine experiments were carried out on a downsized PFI twin-cylinder SI engine, equipped with an electro-hydraulic intake variable valve actuation system (VVA) that allows to manage the combustion air with a limited throttling of the intake duct at part load. The engine, whose main details are represented in Table 1, includes a waste-gated Mitsubishi turbocharger, with a dump-valve for surge control on the compressor, allowing boost pressures up to 2.4 bar. The combustion air to the engine was constantly supplied at 293±1 K by an air conditioning unit. The engine was equipped with piezo-quant

pressure transducers (accuracy of $\pm 0.1\%$) to detect in-cylinder pressure signal within both cylinders. Instantaneous in-cylinder pressure signals on 270 consecutive cycles were acquired by the AVL INDICOM, allowing to estimate the related ensemble averages and the post-processing analyses. Furthermore, the boost pressure at the compressor outlet and the turbine inlet pressure were acquired through piezo-resistive low pressure indicating sensors. The engine was also equipped with thermocouples to monitor the intake and exhaust temperatures primarily to check the maximum gas temperature allowed to the turbine blades.

Table 1. Engine main characteristics

PFI Twin-cylinder Engine	
Displacement [cm ³]	875.4
Layout	4 valve/cyl
Bore [mm]	80.5
Stroke [mm]	86
ConnectingRodLength [mm]	136.85
Compression ratio	10:1
RatedPower [kW]	63.7@5500rpm
Max Torque [Nm]	146.7@2000rpm

The engine, fuelled by gasoline 95 RON EN228, was controlled by a prototype driver managed by a software tool developed within LabView environment, able to switch from the commercial ECU to external control. In this way, the main engine parameters, such as spark advance (SA), timing and interval of fuel and water injection were handled and monitored. On the other hand, the standard ECU, based on manufacturer-developed logics, controls valve and turbocharger strategies. The fuel injection amount was fine monitored to realize the correct air/fuel ratio, estimated by the exhaust lambda sensor upstream of the 3-way catalyst. The in-cylinder pressure data were acquired selecting a high sampling resolution of 0.1 CAD within the angular window between -90 and 90 CAD ATDC, for combustion analysis assuming a polytropic thermodynamic process. Outside the former angular interval, the sampling resolution was set at 1 CAD.

Water Injection System

The layout of the water delivery system includes a commercial liquid pump to pressurize the water at 4 bar and a rail to accumulate a proper amount of water upstream of the injectors. The rail pressure was kept constant by a regulator by draining the surplus water to two commercial solenoid injectors that were installed in the runners, upstream of the standard gasoline ones. The management of the water injection system was controlled by the external driver that also allowed to handle the water injection timing and interval. The water was injected, at the temperature of 298 K, at the same timing as the gasoline.

Engine Test Conditions

Tests were carried out from 2500 to 4500rpm with a step of 500rpm, WOT conditions and load levels in the medium/high range 18-16.4bar net IMEP, corresponding to the base gasoline conditions. The net IMEP was estimated by the in-cylinder pressure over the complete engine cycle, that is the difference between the gross IMEP,

estimated by in-cylinder pressure over compression and expansion strokes, and pumping mean effective pressure (PMEP) evaluated over intake and exhaust strokes. The IMEP level was limited to keep the maximum allowable Turbine Inlet Temperature (TIT) below 950°C, and the average maximum in-cylinder pressure below 85bar (± 5 bar) that is the maximum allowable peak pressure to preserve the engine from mechanical failure of components. To this aim, the maximum boost level was automatically controlled in the range 1.8-2.0bar, acting on the waste-gate valve opening. All the tested engine speeds and loads were representative of a full-lift intake valve actuation. The engine coolant temperature was set at about $90 \pm 1^\circ\text{C}$, by using a water heat exchanger, for any operative condition.

Table 2. Test conditions

Speed [rpm]	SA [CAD ATDC]	W/G [%]	SOI _G =SOI _W [CAD ATDC]	λ [± 0.01]
2500	-8	0	-140	0.89
2500	-9 to -11	0.2	-140	1.00
3000	-8.5	0	-165	0.92
3000	-9.5 to -14.5	0.2	-165	1.00
3500	-12	0	-179	0.89
3500	-13 to -17	0.2	-179	1.00
4000	-13	0	-199	0.92
4000	-14 to -19	0.2	-199	1.00
4500	-14	0	-233	0.89
4500	-15 to -21	0.2	-233	1.00

Relative air-fuel ratios (λ), for the reference cases (full gasoline conditions), were those set by the standard ECU map to avoid knock occurrence at low engine speed and to limit the exhaust gas temperature at higher speed (TIT $\leq 950^\circ\text{C}$). At full gasoline conditions, the λ values, measured by a lambda meter based on the changing oxygen mass and located at the exhaust upstream of the three-way catalyst, ranged between 0.89-0.92 at the different engine speeds. The λ values were kept constant during the tests by fine tuning of the injected fuel amount. The overall test matrix is illustrated in Table 2; the spark advance at the reference gasoline cases (W/G=0) was relative to the most advanced one without knock, whereas a sweep was carried out for W/G=0.2.

Results and Discussion

Thermodynamic Analysis of WI Influence on Engine Combustion and Performance

As already mentioned in the test condition paragraph the reference gasoline cases, in terms of air fuel ratios and spark advance, were chosen according to the standard engine map set by the ECU. As the water was injected, the amount of gasoline was changed up to reach the stoichiometric condition ($\lambda=1$). After that a spark timing sweep was carried out up to the detection of the knock limited condition. This procedure was followed for any engine speed advancing by one crank angle degree the spark timing referred to the full gasoline case at knock limited conditions, identified on the evaluation of the well-known MAPO index [20] for each individual cycle.

Concerning the overall engine performance, Figure 1 shows the net IMEP profiles as a function of the spark advance from 2500 to 4500rpm at the water mass fraction of 0.2 and $\lambda=1$. The figure shows that the IMEP constantly increases as the spark timing is advanced almost reaching the corresponding value provided by the base gasoline case (star symbols). The enhanced heat subtracted by the water evaporation produced a better knock resistance but the engine was even now running knock limited at any speed because the SA attaining the MBT is located at earlier spark timings. The advance in the spark timing provided by the WI gives further advantages on cycle to cycle variability and exhaust gas temperature, as it will be shown in the following plots.

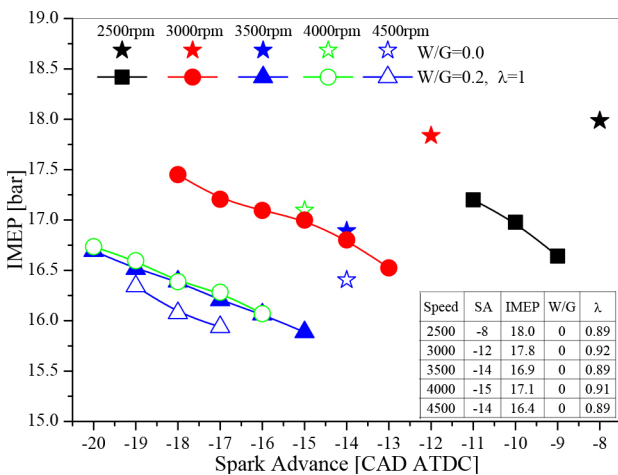


Fig. 1. Indicated Mean Effective Pressure against spark advance in the interval of engine speed from 2500 to 4500rpm.

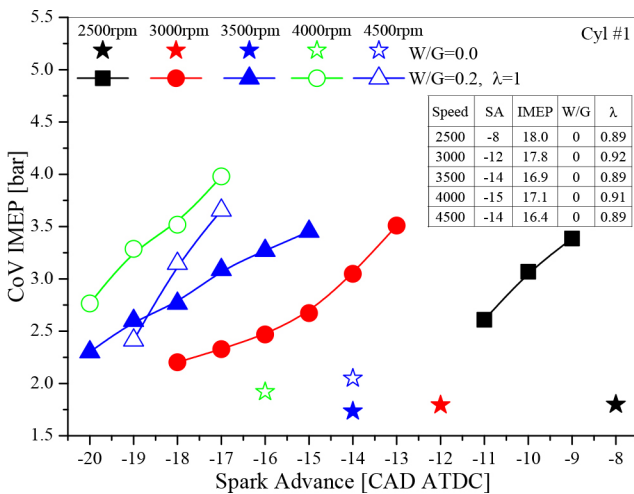


Fig. 2. CoV IMEP against spark advance in the interval of engine speed from 2500 to 4500rpm.

Considering that low cyclic variability may reduce intrinsically the knock tendency because of a lower dispersion between slow and fast cycles, the influence of water injection on the CoV IMEP was also estimated. The results are reported in Figure 2 as function of the spark timing, at different engine speeds. Compared to the full gasoline condition, the WI induced a worsening of the CoV IMEP mainly due to the effects of water dilution and slower burning velocities. On the contrary, a decreasing trend along the spark

advance was observed with values below 3% at the KLSA conditions. This result guarantees a behavior comparable to the gasoline reference cases with acceptable combustion stability all over the engine operating points.

Regarding the effect of WI on the in-cylinder pressure peak, Fig. 3 reports the peak pressure profiles versus the combustion phasing (MFB50) for the cylinder #1. It is interesting to observe that the peak pressure shows a linear increasing profile against the combustion phasing at advanced spark timing, with a high correlation rate at any engine speed. Even though the spark timing was significantly advanced, a limited increase in the combustion pressure peak was attained, remaining below the threshold limit of 85bar. The limited raise in the pressure peaks, allowed by the slower burning rate that results in a longer combustion interval, did not determine a severe mechanical stress compared to the reference cases.

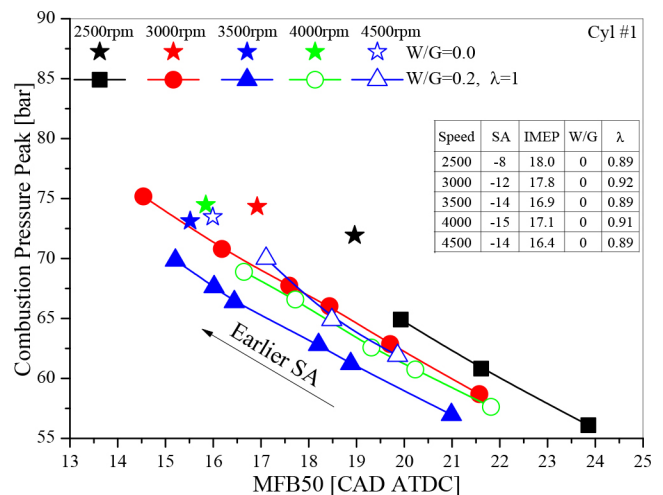


Fig. 3. In-cylinder pressure peak against spark advance in the interval of engine speed from 2500 to 4500rpm.

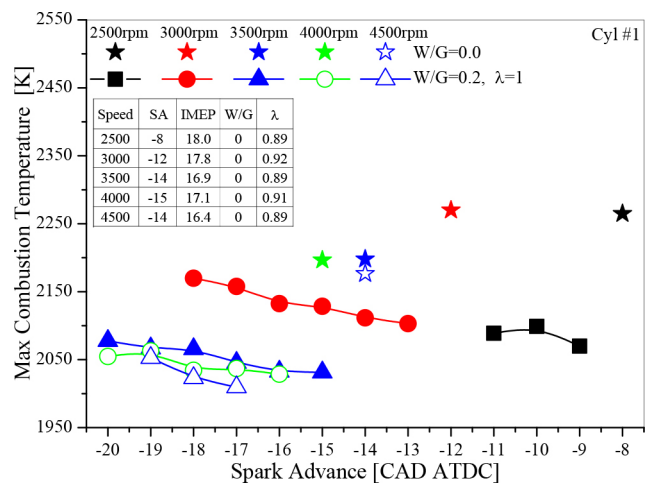


Fig. 4. Combustion temperature peak against spark advance in the interval of engine speed from 2500 to 4500rpm.

Figure 4 shows the behavior of the combustion peak temperature against the spark advance. The estimated in-cylinder gas temperature was computed from the measured in-cylinder pressure assuming a