

Water Injection to Enhance Performance and Emissions of a Turbocharged Gasoline Engine under High Load Condition

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ABSTRACT

The potential benefits of water injection on performance and emissions were investigated on a downsized PFI twin-cylinder turbocharged spark ignition engine. Experiments were carried out at high load condition (~ 15.5 bar IMEP) within the engine speed range from 3500 to 4500rpm with a step of 500 rpm. For each test case the effect of the injected water quantity on combustion and exhaust emissions was investigated by sweeping from 10%w to 30%w the water to gasoline ratio. The water was injected at the same timing as the gasoline by a low pressure injection system external controlled. Tests were performed at WOT conditions exploring, for each operating condition, a spark sweep from knock-free up to knock-limited operation.

Compared to the full gasoline reference case, the water injection allowed to advance extensively the spark timing without knock occurrence. The 20% water to gasoline mass fraction gave the best improvements in terms of IMEP. The reduction of combustion temperature, due to the water injection, coupled to the spark timing advance without knock, led to a stable reduction of the temperature at the turbine inlet.

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INTRODUCTION

Despite the continuous advancement of spark ignition engine technology, further solutions are under investigation to improve fuel efficiency and meet worldwide CO₂ emissions regulation [1,2]. Currently, engine manufacturers have focused on engine downsizing to improve combustion efficiency with the introduction of turbocharger or higher compression ratio engines that have the drawback to run the engine at delayed spark advance or richer mixture due to the knock occurrence. Downsized engines have the advantage to achieve high efficiency at part load, particularly engines equipped with VVA/VVT systems. The full load performance is then enhanced because of turbocharger actuation. One of the main restrictions to further improve efficiency, mainly under high loads conditions, is the occurrence of abnormal combustion due to a combination of temperature and pressure history of the end gas and the speed of combustion flame [3,4,5]. As soon as the temperature and pressure of the end gas exceed its auto-ignition point, the end gas would ignite abruptly with intense pressure fluctuations and velocities that may rise above 2000 m/s. A lot of literature is available on the knock characterization with studies made both on commercial and optically accessible engines [6,7,8,9,10]. Regarding conventional downsized turbocharged engines, several technologies have been implemented to improve the efficiency and mitigate knock, as for example high boosting, direct injection, lean burn mechanism or internal EGR. Further, knock and pre-ignition tendencies can be

reduced, compared to internal EGR, through external cooled EGR because the concentration of radicals in the exhaust gas is reduced by the effect of lower temperature [11,12,13].

The increased probability of knock, or pre-ignition are usually handled by retarded spark advance or fuel enrichment at high load and engine speeds. More recently, experimental studies are under investigation with the adoption of water injection that may provide improvements in the efficiency of spark ignited engines and mitigate knock conditions. In fact, taking advantage of the high latent heat of vaporization of the water introduced into the cylinders an appreciable cooling of the charge can be obtained. Besides, the reduced rate of the compression temperature contributes to lessen the maximum temperature with benefits on the anti-knock behavior. In addition to knock resistance when combined to boosted engines, the water injection also has a positive impact on exhaust gas temperature at high load and engine speed with improved torque. The potential benefits to obtain a reduction of the charge temperature is related to the latent heat of vaporization that for the water is 2250 kJ/kg much higher than that of gasoline (300 kJ/kg). Another potential candidate might be methanol that has a latent heat of vaporization of 1100 kJ/kg higher than that of gasoline and this, together with the high octane number (~ 110), is advantageous for the purpose of performance and knock improvement.

In the current literature a few papers have been published to report the potential of water injection to mitigate knock or reduce the enrichment of air-fuel mixture at high engine speed and load [14,15]. Further, in a recent article Kim et al. [16] investigated the effects of water directed injected within the cylinder to enhance torque and fuel consumption at high load. Tests with water addition were performed in the range of engine speed of 1500-3000 rpm achieving an improvement in the brake specific fuel consumption, a reduction in in-cylinder and exhaust gas temperature. The increase in the injected water mass allowed to set advanced spark timing without knock occurrence that made possible a further fuel reduction.

Hoppe et al. [17] made an experimental investigation on the potential of water injection on a DI spark ignited single cylinder research engine, homogeneously operated, equipped with a Miller cycle and cooled external EGR. The condensate water recycled from the exhaust gas, cooled down to its dew point was directly injected within the cylinder. The advantages obtained from this concept was an increase in the thermal efficiency by about 3.3-3.8% in the region of minimum brake specific fuel consumption with a further improvement running the engine with the Miller cycle and lean burn condition.

Busuttil and Farrugia [18] addressed the potential of water injection in a prototype single cylinder engine equipped with a port fuel injection and a low pressure water injection, set at the intake pipe. The results of investigation showed as the management of spark timing allowed the engine to run without knocking.

Concerning the water injection investigation from a numerical point of view few papers are currently available [19,20,21]. In particular, Bozza et al. [20] investigated the potential of cooled EGR and water injection in a PFI turbocharged SI engine at full load knock limited operation. A 1D approach was followed in order to investigate at different operating engine points, full load and different speeds for various A/F ratios, the influence of water injection on fuel economy. The numerical results showed that the water injection made possible important brake specific fuel consumption reductions, with respect to the base calibration, under operating points at 2100rpm@20Nm, 2500rpm@21Nm and 3300rpm@21Nm.

Berni et al. [21] evaluated, by 3D-CFD numerical analysis, 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.

In this paper, the water injection technology was experimentally investigated with the aim to reduce the fuel consumption, the inlet turbine temperature and enhance the knock limit. This investigation has the final objective to use the injection of water, water injection port (WIP), to achieve the same torque and detonation limit of an engine running with rich mixture, but injecting a stoichiometric amount of fuel. The main target is to reach the maximum combustion efficiency, reducing the turbine inlet temperature and fuel consumption.

EXPERIMENTAL SETUP

Engine experiments were carried out on a downsized PFI twin-cylinder SI engine, equipped with an electro-hydraulic intake valve actuation system (VVA). It 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.

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
Connecting Rod Length [mm]	136.85
Compression ratio	10:1
Rated Power [kW]	63.7@5500 rpm
Max Torque [Nm]	146.7@2000 rpm

The intake air to the engine was constantly supplied at 293 K by an air conditioning unit. The engine was equipped with piezo-quartz pressure transducers (accuracy of $\pm 0.1\%$) to detect in-cylinder pressure signal within both cylinders. Pressure signals were acquired by the AVL INDICOM, allowing in-cylinder combustion and post-processing analyses. Furthermore, the boost pressure and the upstream turbine pressure were acquired through piezo-resistive low pressure indicating sensors located at the compressor outlet and exhaust manifold. 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. A sketch of the engine test bench is shown in Figure 1.

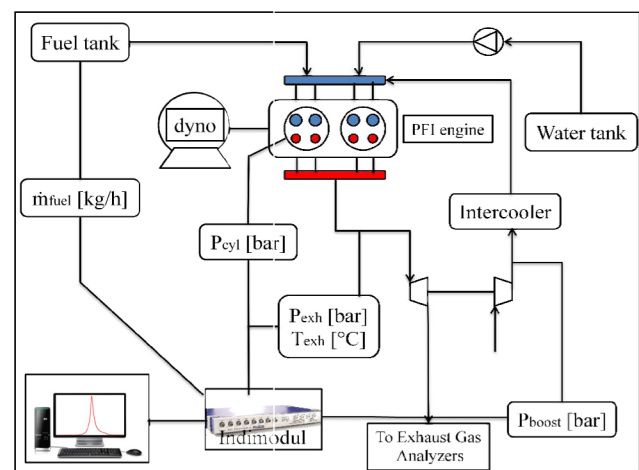


Figure 1. General layout of the experimental setup.

The engine was controlled by a prototype driver managed by a software tool developed within LabView environment, able to switch from the reference commercial ECU to external mode [22]. In this way, the main engine parameters, such as spark advance (SA), start and interval of fuel and water injection were handled and monitored.

The fuel injection amount was fine monitored to realize the correct air/fuel ratio estimated by the signal from the exhaust lambda sensor. 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 is sketched in [figure 2](#). It 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 the gasoline ones.

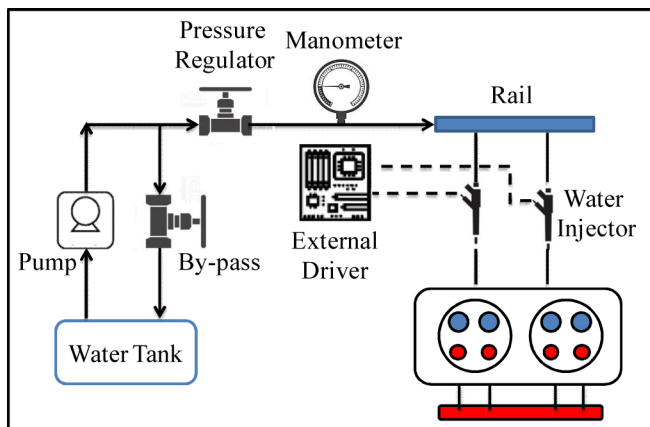


Figure 2. Water injection system.

The management of the water injection system was controlled by the external driver that also allowed to manage the water injection timing and injection interval. The water was injected, at the temperature of 25°C, at the same timing as the gasoline and a sweep on the water to gasoline ratio was investigated from 0.10 up to 0.30 mass fraction, as shown in [Table 2](#). The effects of water injection on knock mitigation were investigated over the engine speed range 3500-4500 rpm, advancing the spark timing, at constant value of λ , up to knock occurrence.

Engine Test Conditions

Tests were carried out at 3500, 4000 and 4500 rpm, WOT condition, and load levels in the medium/high range 15-16 bar, net IMEP, at full gasoline conditions (95 RON EN228). The IMEP level was limited to keep the maximum allowable Turbine Inlet Temperature (TIT) below 950°C, and the maximum in-cylinder pressure below 85 bar that is the maximum allowable peak pressure suggested by the manufacturer to preserve the engine mechanical breakdown of the components. To this aim, the maximum boost level was automatically controlled by the ECU in the range 1.9-2.0 bar, acting on the waste-gate valve opening. The selected engine speeds and loads were representative of a full-lift intake valve actuation. Valve timings keep on constant at each test case so that the potential engine performance improvements can be ascribed only to the effect of water injection. The engine coolant temperature was about 90°C for any operative condition.

Relative air-fuel ratio, λ , set by the ECU map in the range 0.89-0.93, was monitored by a O2 sensor at the exhaust, upstream of the 3-way catalyst, and kept constant during the experiments by fine tuning of the injected fuel amount. For the test cases, the engine runs under knock limited conditions and although the combustion is close to an optimal angular position (MFB50), the A/F ratio, at high speed and load, is enriched to limit the exhaust gas temperature ($TIT \leq 950^\circ\text{C}$).

The most advanced spark time was controlled to avoid knock occurrence in each cycle. The adopted approach, for knock detection, was based on the MAPO index that analyzes the characteristic high frequency fluctuations of the in-cylinder pressure signal [23, 24]. The in-cylinder pressure signal was windowed in the interval (-90, 90 CAD), filtered by a Butterworth high-pass filter at 3.5 kHz and rectified in order to define the maximum value of the pressure oscillations according to the following definition:

$$\text{MAPO} = \max(|\hat{p}|)$$

where $|\hat{p}|$ is the filtered and rectified in-cylinder pressure signal. Although knock threshold depends on each specific engine and operating conditions, a linear increasing threshold, due to the increase of the signal to noise ratio with the engine speed, was initially defined in the interval (1000, 5500 rpm) and steadily adjusted. To experimentally determine the KLSA, an acceptable percentage of knocking cycles was set equal to 2%. Based on this value, a statistical analysis was carried out, in order to calibrate the threshold in the whole range of engine operative speeds. The threshold limits were set equal to 1.2 and 1.8 bar at 2000 and 4500 rpm, respectively.

The overall experimental test matrix is illustrated in [Table 2](#), where the IMEP value is relative to the most advanced spark timing without knock at full gasoline conditions.

Table 2. Test conditions

Speed [rpm]	SA sweep [CAD ATDC]	IMEP [bar]	W/G [%]	SOI ₆ =SOI _W [CAD ATDC]	λ [±0.01]
3500	-12 to -17	15.3	10,20,30	-179	0.90
4000	-13 to -19	15.7	10,20,30	-199	0.93
4500	-14 to -21	15.1	10,20,30	-233	0.89

RESULTS DISCUSSION

This paragraph first illustrates the procedure pursued to set the reference spark timings at full gasoline operative conditions, as shown in [Table 2](#). They were selected as the most advanced spark timings in which, at each tested engine speed, no knock event was recognized.

[Figure 3](#) reports the MAPO index results for the investigated test cases, full gasoline condition, at the spark timing of the knock event occurrence and that without knock. Plots report the ensemble of MAPO index versus the peak pressure for the cylinder #1 and #2, being both interested by the knock onset. It is well displayed as the advance of only 1 CAD causes a knock event, remarkably strong at each engine speed. A rising MAPO profile is well represented as function of the in-cylinder peak pressure, being the peak pressure one of the parameters linked to a higher occurrence probability of abnormal combustion. In addition, the above considerations and the