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Effects on knock intensity and specific fuel consumption of port water/methanol injection in a turbocharged GDI engine: Comparative analysis

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Abstract

The recent rise in fuel prices, the need both to reduce ground transport-generated emissions (increasingly constrained by legislation) and to improve urban air quality have brought fuel-efficient, low-emissions powertrain technologies at the top of vehicle manufacturers' and policy makers' agenda. To these aims, engine design is now oriented towards the adoption of the so-called downsizing and down-speeding techniques, while preserving the performance target. Therefore, brake mean effective pressure is markedly increasing, leading to increased risks of knock onset and abnormal combustions in last-generation SI engines. To counterbalance the increased risks of pre-ignition, knock or mega-knock, currently made turbocharged SI engines usually operate with high fuel enrichments and delayed (sometimes negative) spark advances. The former is responsible for high fuel consumption levels, while the latter induce an even lower A/F ratio (below 11), to limit the turbine inlet temperature, with huge negative effects on BSFC. Possible solutions to increase knock resistance are investigated in the paper by means of 3D-CFD analyses: water, water/methanol emulsion and methanol are port-fuel injected to replace mixture enrichment while preserving, if not improving, indicated mean effective pressure and knock safety margins. The aim of the work is therefore the replacement of the gasoline-only rich mixture with a global stoichiometric one while avoiding power loss and improving fuel consumption. In order to maintain the same knock tendency, water, methanol or a mixture of the two is then added in the intake port to keep the same charge cooling of the original rich mixture. Different strategies in terms of methanol/water ratios of the port injected mixture are compared in order to find the best trade-off between fuel consumption, performance and knock tendency.

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Keywords: Downsizing, Methanol,Water,Knock

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1.Introduction

A new generation of highly downsized SI engines with specific power output around or above 150 HP/liter is emerging in the sport car market sector. Technologies such as high-boosting, direct injection and downsizing are adopted to increase power density and reduce fuel consumption. To counterbalance the increased risks of pre-ignition, knock or mega-knock, currently made turbocharged SI engines usually operate with high fuel enrichments and delayed (sometimes negative) spark advances. The former is responsible for high fuel consumption levels, while the latter induce an even lower A/F ratio (below 11), to limit the turbine inlet temperature, with huge negative effects on BSFC. Some possible countermeasures were investigated in previous works by the authors using CFD-3D analyses. In particular, the potential advantages which can be gained replacing fuel enrichment with water [3,4] or with Methanol-Water emulsions (called MW) [5] on BSFC and knock tolerance of a currently produced V8-GDI engine were shown. In this work methanol, methanol-water or water are injected in the intake ports through an 8 hole PFI injector. Thanks to the charge cooling provided by the "second injection" it is possible to obtain the same in-cylinder temperature at spark time of the gasoline-enriched original case. A consistent reduction in fuel consumption is made possible by introducing in the combustion chamber a stoichiometric-only mixture. From the knock tendency point of view some different aspects must be considered: water acts as an EGR species and its introduction in the combustion chamber on one hand reduces the chemical reactivity of the end-gas while, on the other hand, promotes knock occurrence by reducing the burn rate. Different considerations are related to methanol, which is characterized by higher octane number and laminar flame speed than that of pure gasoline. Its presence shows a potential benefit in reducing knock tendency and, thanks to the higher energy density per oxidizer unit, in improving performance output. Moreover the higher methanol volatility can improve the evaporation of the PFI mixture in low rpm and part load operating conditions where the reduced charge temperature and turbulence intensity prevent a complete evaporation of the pure-water injection [4]. However, the addition of a second fuel such as methanol promotes end-gas reactivity. The aim of the work is the evaluation of the potential benefit deriving from the replacement of the gasoline-only rich mixture with a stoichiometric one preserving the same power output and improving the specific fuel consumption. In order to maintain the same knock tendency, water, methanol or a mixture of the two is then added in the intake port to obtain a comparable charge cooling as the original rich mixture. Several methanol/water ratios of the port injected mixture are numerically evaluated in order to find the best trade-off between fuel consumption, performance and knock tendency.

2.Numerical Setup

The 3D CFD analyses presented in this paper are carried out by means of a customized version of Star-CD v4.22, licensed by CD-adapco. Time varying pressure and temperature boundary conditions are derived from a tuned 1-D model supplied by engine manufacturer and are the same for all cases. The adopted turbulence model is the k-ε RNG for compressible flows. The computational mesh used in the 3D simulations covers half of the combustion system, thanks to the geometrical symmetry and the RANS framework used in this study. The total number of fluid cells is about 450000 and 250000 at BDC and TDC, respectively. For the high-pressure fuel injection simulation, a pre-atomized population of Lagrangian particles is assigned to each of the 7 injector nozzles. The secondary break-up is modelled by means of the Reitz model [6] while for droplet wall interaction the Bai approach [8] is adopted. For the simulation of the injected methanol-water solutions an analogous strategy is used for both primary and secondary break-up, while injection pressure for the liquid phase is limited to 5 bar. This value is chosen in agreement with experimental datasets found in literature for PFI systems [8, 9]. The methanol-water

emulsions used in the analyses are three, namely MW25, MW50 and MW75 with increasing methanol ratios (respectively 25%, 50%,75% by mass fraction). They are modelled as a multi-component liquid with temperature dependent physical properties derived from the NIST database. The adopted combustion model is the ECFM-3Z [11], which has been widely used in previous publications by the authors [12, 13, 14]. In order to account for multi-fuel combustion, at spark onset the two fuels are lumped into a unique scalar, whose properties are those of an equivalent fuel species. Given the low percentage of methanol (whose concentration is always lower than 5%) and considering its almost homogeneous distribution, an assumption of linear-by-volume properties is made for the equivalent fuel. Density, molecular weight, lower heating value, air-to-fuel stoichiometric ratio and specific heat are then computed as the mass-weighted average of those of each fuel component . Finally, the laminar flame speed of the equivalent fuel is also modified accordingly, using the same mass-average concept and by adopting the correlations for pure iso-octane and pure methanol proposed by Metghalchi and Keck [10]. An in-house procedure is applied in this paper also for the modelling of knock, which is extensively described in previous publications [12] and which is based on a detailed tabulation of the autoignition delays from chemical kinetic simulations. The mechanism used for the presented analyses is the 138-species TRF (Toluene Reference Fuel) scheme by Andrae et al. [15], here adopted to reproduce the anti-knock quality of the RON-98 gasoline used in the experiments. Methanol presence is also considered in the fuel surrogate model. The input for the knock model is a 5-variable vector $\psi = \psi(p, T, \phi, EGR, Y_M)$ of the local and instantaneous physical state of each fluid cell and the methanol concentration; a cell-wise delay is then multi-linearly interpolated from the look-up tables.

3.Preliminary analysis

The purpose of this paper is to substitute the gasoline enrichment of the reference engine with a stoichiometric mixture of gasoline, methanol and water. However, the addition of a secondary fuel (methanol) needs to be considered for a given trapped air quantity, i.e. for a fixed oxidizer mass. Therefore, the injected mass of methanol and water are calculated in order to maintain a global stoichiometric ratio and to provide the same charge cooling supplied by fuel excess obtaining same in-cylinder temperature at the start of combustion of the reference case. Pure methanol, pure water and three blends of the two are considered in the presented analyses: MW25, MW50 and MW75. In order to carry out a realistic evaluation, these blends are injected in the intake port so that the cylinder dome is not modified. Methanol-water mixtures are injected by means of a simple low-pressure injection system whose characteristics are derived from standard low pressure PFI gasoline. These conditions are imposed in order to compare the results with the original gasoline-only case as in [5], adding at the “cooling condition” also a comparable compression heating constraint by considering the different specific heat capacities of the mixtures.

The results of the preliminary calculations are shown in Fig.1(a). Moving from the water-only to the pure methanol case the injected gasoline mass is reduced to obtain a stoichiometric mixture. By increasing the methanol fraction of the PFI emulsion leads to an increase of the total secondary-injected quantity in order to produce the same charge cooling. This is due to the lower latent heat of vaporization of methanol compared to water. Moreover, it is possible to notice that also the total fuel quantity increases by moving from the only-water to the only-methanol case: this is due to the lower air-to-fuel stoichiometric ratio of the methanol compared to gasoline. The different properties of the two fuels are responsible for the properties of the equivalent surrogate fuel, as shown in Fig.1(b). An increase of methanol quantity in the combustion chamber leads to higher fuel-to-air stoichiometric ratio and to a reduction of the lower heating value. Nevertheless the larger total fuel quantity allows to recover the gap

in terms of total heat releasable by combustion, which can be considered as constant in these analyses (it is slightly higher by ≈1% in the methanol-only case).

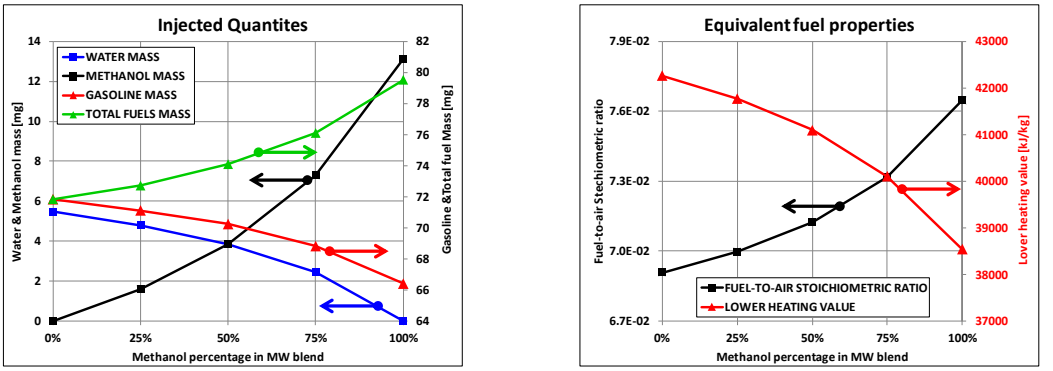

Fig. 1. (a) Injected quantities of gasoline, methanol and water; (b) Fuel to air stoichiometric ratio and lower heating value of equivalent fuel as a function of the methanol percentage in MW blend.

4.Investigated Engine and operating conditions.

The investigated engine is a currently produced 8 cylinder V-shaped direct injection spark ignition (DISI) turbocharged unit (displacement ≈ 3800 cm^3, Maximum Power > 400 kW at 7000 rpm). The engine is analyzed at peak power engine speed, W.O.T. For this engine condition and for the gasoline-only case, the CFD models for each of the lagrangian spray, the combustion heat release and the knock proximity were deeply investigated and calibrated by the authors in previous publications [12,13].

5.Results and discussion.

A comparison between all the strategies, under the same spark advance as the original gasoline-only case, is here carried out. From the in-cylinder pressure traces and combustion progress, reported in Fig.2(a), it is possible to notice an improvement of burn rate by increasing the methanol percentage in the MW emulsion. The IMEP results show an upward trend as visible in Fig.2(b). An enhancement higher than 10% in ISFC compared to the gasoline-only case is obtained for all the mixtures. The less advantageous case is the methanol-only case: in order to reach the same charge cooling effect and completely consume the oxidizer, the total fuel quantity is higher. This is the reason why, despite the increased IMEP, an increase in ISFC is measured. Considering the in-cylinder temperature traces, reported in Fig.3(a), it is visible that the charge cooling condition is met. At spark time the average in-cylinder temperature is the same for all the analyzed cases and the difference with the gasoline-only case is about 8K (≈1%). However, large temperature differences during the power stroke can be noticed comparing the gasoline-only rich case with all the stoichiometric ones. In the methanol-poor cases (Water, MW25 and MW50) these effects are due to the retarded development of combustion while in the MW75 and in the methanol-only cases this is due to the higher temperature peak reached. Autoignition is tracked as soon as the knock precursor concentration (YIG) locally equates the fuel tracer concentration (YTF.) It is then possible to define a Knock Tolerance scalar function, as the local difference between the fuel tracer and the precursor: Knock Tolerance $(\vec{x}, t) = \mathrm{YTF}(\vec{x}, t) - \mathrm{YIG}(\vec{x}, t)$. In Fig.3(b) the lower local value of "Knock tolerance" in the end gas is reported. When this quantity approaches zero the local

physical conditions for autoignition are met. All the stoichiometric cases are characterized by higher knock resistance in comparison with the gasoline-only one, while the worst case is still the methanol-only one due to the high temperature level reached during combustion. The spark advance is increased in order to limit the in-cylinder temperature during the compression stroke and to obtain a comparable performance and to preserve a knock safety margin. As reported in Fig.4(a) all the cases reaches about the same knock tolerance, higher than the reference case. In the methanol-poor cases the spark advance increase in order to reach the same knock tolerance is higher: this leads to lower in-cylinder temperature at exhaust valve opening (Fig.4(b)). Finally, approximately the same IMEP is measured for all the cases with increased SA, as illustrated in Fig.5(a): given the comparable output performance, it is then possible to draw coherent conclusions regarding the improvement in specific fuel consumption. It is evident in Fig.5(a) that the case with pure water is the one leading to the lowest ISFC, with the pure-methanol one being the one with the highest ISFC. Finally, the measured IMEP and ISFC values for all the cases compared to the gasoline-only condition allow to assess a roughly constant 4% improvement in IMEP, while reduction in ISFC is as large as 20% for the water-only case.

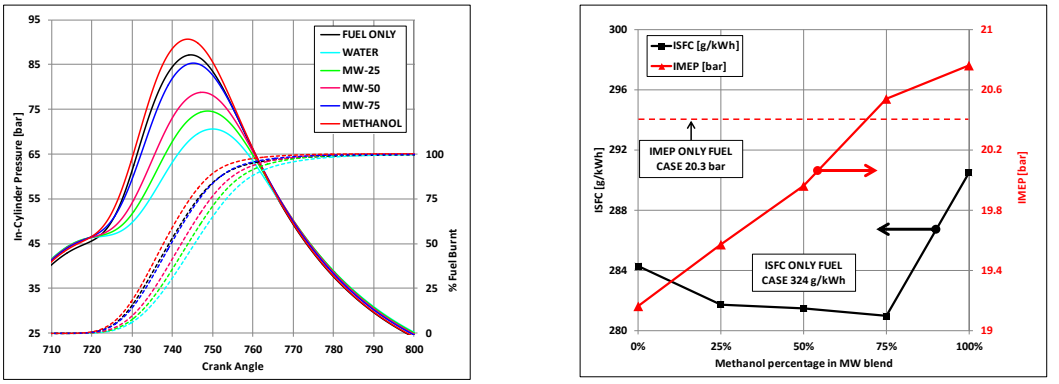

Fig 2:(a) In-cylinder Pressure (continuous lines), % Fuel Burnt (dashed lines) 720CA=TDCF; (b) Indicated Specific Fuel Consumption (black) and Indicated Mean Effective Pressure (red); for all the investigated cases with same spark advance.

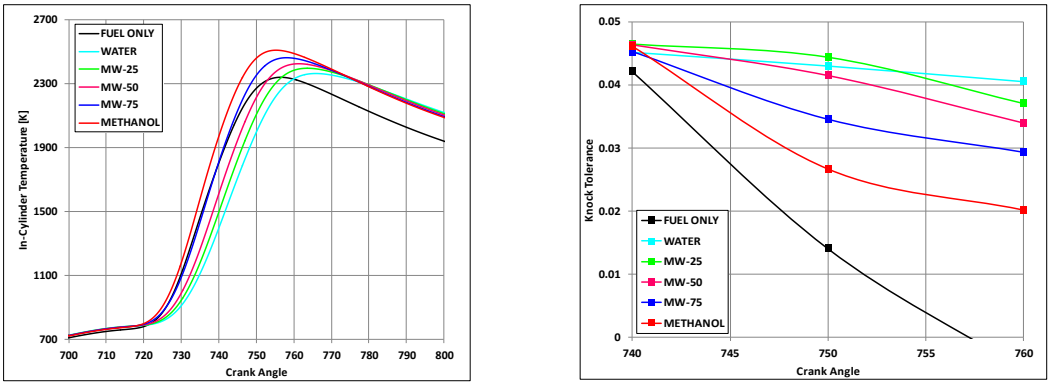

Fig 3(a) In-cylinder temperature trace 720CA=TDCF; (b) Knock Tolerance; for all the investigated cases with same spark advance.

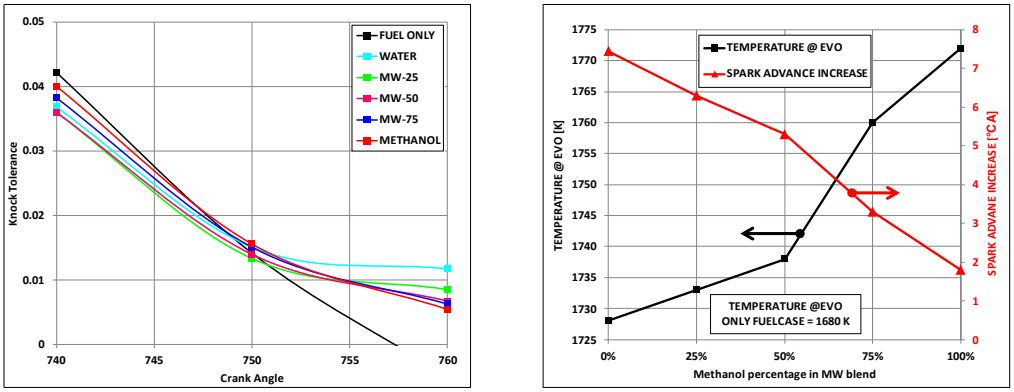

Fig 4 (a) Knock Tolerance; (b) In-Cylinder-Temperature at EVO (black line) and Spark advance increase (red line); for all the analyzed cases.

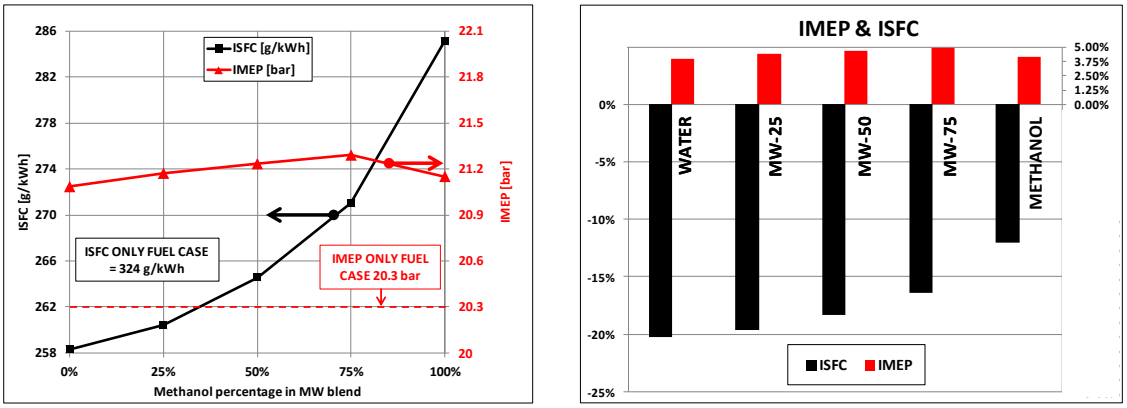

Fig 5(a) ISFC [g/kWh] and IMEP [bar]; (b) Percentage variation of IMEP and ISFC in comparison with only fuel case; for all the analyzed cases.

6.Conclusions.

In the paper, the potential as knock suppressor of port-injected methanol-water mixtures and water are numerically evaluated on a currently produced high-turbocharged DISI engine, whose knock tendency was extensively studied by the authors in the past years. Three different MW mixtures with different methanol-water ratio are injected at knock limited, peak power operating condition (7000 rmp) characterized by large fuel enrichment to limit knock tendency. The aim of the analyses is to replace the rich mixture with a stoichiometric one adding PFI mixtures to simultaneously subtract the same amount of heat as the removed fuel. At the analysed operating condition the best strategy seems to be the injection of pure water, which leads to the lowest ISFC. Very similar results are obtained also in the low-methanol cases (MW25,MW50), which may result the best strategies at lower rpm conditions due to the higher evaporation rate. This statement is actually under investigation by the authors.

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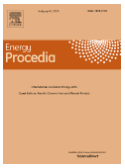

Biography

Sebastiano Breda (born September 26, 1988). Master degree in automotive engineering in 2014 at Modena university. Nowadays Phd student in Phd school: "Ingegneria Industriale e del territorio Enzo Ferrari". Research field: CFD simulation of internal combustion engine; particularly LES approach in order to keep ICE cycle to cycle variability.