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# Fuels with low octane number: water injection as knock control method

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## Abstract

The present paper deals with the study of water effect on the combustion of fuels with low Octane Number in Internal Combustion Engines. In particular, this study was carried out using a variable volumetric compression ratio CFR fuel engine.

ASTM Standards for Motor and Research methods were followed to determine fuels and fuel-water mixture Octane Number.

CFR fuel engine intake manifold was modified to install water injection. Different water/fuel mass ratios were used and Research and Motor Methods Octane Number and pollutant emissions were measured. In particular, water to fuel mass flow ratio was imposed from 0 to 1.5.

Increasing the water/fuel mass ratio an increment in octane number was registered and this behaviour is evident for each base octane number studied. At the same time a reduction in the NO<sub>x</sub> emissions was registered due to both in-cylinder temperature reduction and water chemical interaction with NO<sub>x</sub>. Analysing in-cylinder pressure traces highlighted that water presence reduces pressure oscillation within the cylinder engine.

On the basis of the results it is possible to state that water is able to control detonation in the fuel combustion and an increment of the octane number is registered.

Keywords: Petroleum engineering, Energy, Mechanical engineering

## 1. Introduction

Nowadays, in the industrialised Countries the public opinion attention is focused on energy and fuel consumption and environmental impacts of energy production and use [1, 2, 3], mobility systems, as well as on the use of renewable energy sources (RES) and alternative fuels [4, 5].

Nowadays, very low limits about pollutant emissions from passenger car engines are imposed by industrialized Country Governments due to the attention of the public opinion about environmental constraints. Furthermore, it is necessary to study and continuously increase engine efficiency and reducing pollutant emissions produced in combustions [6, 7, 8, 9]. In mid-term, there are uncertainties about global warming and there is the necessity to monitor and reduce CO<sub>2</sub> emissions from combustion systems. In long-term, there is the possibility to have a significant effect on efficiency and on environmental protection at the same time.

Alternative fuels [8] and bio-derivate fuels [10, 11] could be used to reduce the impact of engines on the environment. Different strategies could be used to reduce environmental impact of engine running. Among the strategies, water injection could be one.

Increasing Internal Combustion Engines performance by means of water injection is not certainly a novel concept [12, 13]. Aircraft engines in the 40s [13] and high-power Formula One engines in the 80s [13] used this technique to control knock, increase power and reduce pollutant emissions [14, 15, 16, 17, 18, 19, 20, 21, 22]. In-cylinder or port [14, 16] water injection generally permits higher values of engine compression ratios without occurring in the knock phenomenon. Moreover, water injection allows to obtain highly turbocharged engine downsizing running regularly without knock [21, 22]. The main effect of water injection is to reduce end-gas temperature and cooling the engine combustion chamber [21, 22].

Alcohol, such as methanol, could be used as coolant, but, normally, a mixture of 50/50 water-alcohol is preferable. Traces of water-soluble oil are also introduced into the mixture with the purpose of preventing corrosion of fuel system components. The water is the main coolant due to its high density and heat capacity, while alcohol could be used also as water antifreeze adding at the same time combustible to the engine [16, 19].

Using in-port water injection leads to fuel/air mixture temperature reduction, while a mixture density increase is registered. Definitely the total mass entering the cylinder is higher [23]. Moreover, during combustion water vaporizes absorbing high quantity of heat. This reduces in-cylinder peak temperature that leads to a reduced NO<sub>x</sub> emission [16, 17, 18, 19, 20, 21, 22] as well as the quantity of heat energy wasted

though the cylinder walls. The alcohol is a combustible; thus, it burns during combustion and at the same time has the effect to increase fuel-air mixture knock resistance. Therefore, it is equivalent to have a higher value of fuel O.N. This permits higher values of engine compression ratios without knock [14, 15, 16].

The present paper deals with the study of water injection effects on combustion, Octane Number (O.N.), detonation control and pollutant species formation in Internal Combustion Engines (ICE) from an experimental point of view by means of standard CFR engine. In particular, in the present study a reference fuel was used instead of topping virgin naphtha to increase the repeatability of the results, while a heat realised analysis was carried out to analyse effects on combustion.

## 2. Experimental

In the present paper, standard Research Waukesha CFR Fuel Engines [23] were used to determine Octane Number of tested fuel/water mixtures. Modified intake system was introduced in standard engine for installing an in-port water injector. Reference fuels at 66, 75, 90 and 95 O.N. were used to verify if CFR engine running was not modified by the intake extension introduction. The obtained results highlighted that intake extension with water injector do not affect O.N. measuring [23].

Fuel was introduced into the engine via carburettor using a standard jet with variable hydraulic head, while fuel consumption was measured by means of a volumetric method because of the difficulty of installing a gravimetric measurement system in a standard CFR. Measuring fuel volume variation in specific time interval for different volumetric compression ratio, an average fuel flow rate of 8.6 g/min was registered, while the water was varied from about 4.3 g/min to 12.9 g/min [24].

A port injection system was installed in the CFR engines with a positive displacement water pump, as well as a pressure regulator. Water mass flow rate was adjusted varying injection pressure (0.2–2.5 MPa) and measured using a gravimetric method. Walls wetting was minimized, while water and fuel sprays interaction was avoided.

The choice of installing an in-port water injection system is related to the fact that in the present study liquid water should be enter the cylinder evaporating while the valves are closed. Probably, most of the introduced water evaporates during combustion phase controlling knock phenomena and reducing pollutant emissions at the same time.

Due to the fact that only a little amount of water evaporates in the intake system and that the amount of water is comparable to the fuel one, the effects on the trapped air is negligible.

Main component characteristics of water injection system were reported in Table 1, while in Fig. 1 some photographs of the experimental set-up are shown. Pollutant emissions were registered using a standard Eurotron Green Line 4000 [25].

A Kistler 6061B piezoelectric pressure transducer with a Kistler 5007 charge amplifier, located in the combustion pickup hole, was used for in-cylinder pressure acquisition. Pressure data were recorded, as well as crank angle by a PC equipped with a NI PCI 6221 (250 kS/s) high-speed data acquisition board [26].

### 3. Results and discussion

According to scientific literature, fuel octane number has a strong effect on SI-ICE performance and efficiency [16, 20, 21]. In order to minimise this effect a modification of both engine and refinery processes design is necessary.

One of the goal of the present study is strictly related to the reduction of anti-knock additive substances in gasoline that allows to low fuel industrial costs. Another aspect is related to engine environmental impacts.

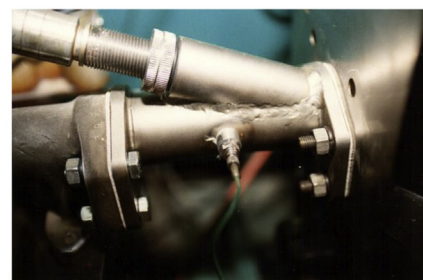
Therefore, several tests were carried out running the CFR engine on different virgin naphtha blends with different base O.N. [15]. In order to measure base O.N., several tests were performed using CFR engine according to Research and Motor Methods [27, 28]. Results of this analysis are shown in Table 2.

**Table 1.** Water injection system main component characteristics.

Description	
Water pump	Bosch 9/100
Pump delivery pressure	10 MPa
Volumetric flow rate	9 dm <sup>3</sup> /min
Pump rotational speed	2800 r/min
Pump power	2 kW @ 2800 r/min
Water nozzle	Delavan 45°



(a)



(b)

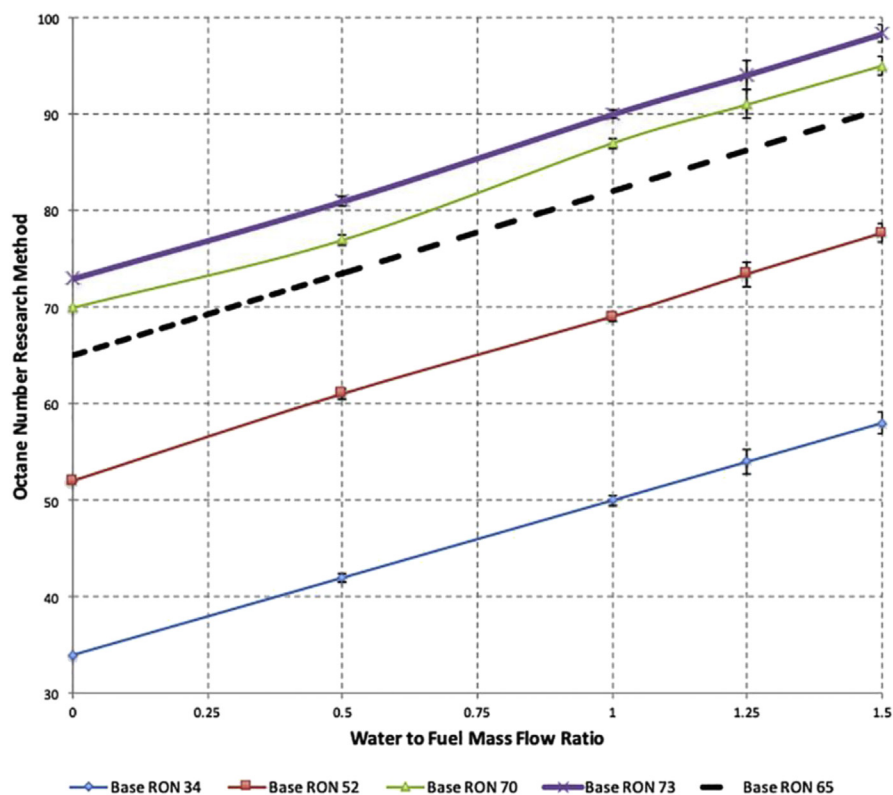
**Fig. 1.** Experimental set-up: (a) CFR Engine, (b) Water intake pipe.

**Table 2.** Base RON for different gasoline blend.

Blend Classification	Base RON
CR30 BL1	34
CR30 BM1	52
CR30 BL2	70
CR30 BL3	73

In order to study the effects of water injection on O.N., fuel-water mixtures were tested in the Waukesha CFR Fuel Engine [23]. Octane Number measurements were carried out using different base gasoline blends (see Table 2) and different water to fuel mass flow ratio (in the range 0–1.5). Water to fuel mass flow ratio was limited to 1.5 because of possible flame quenching.

Water effects on RON are shown in Fig. 2 for different fuel blends as a function of water to fuel mass flow ratio. It is well observed that increasing water to fuel mass flow ratio yields to an almost linear increase of octane number. This behaviour is observed for all studied base octane numbers. As it is possible to observe in the graph in Fig. 2, the higher the water to fuel mass flow ratio, the higher the Octane Number. Starting from a water to fuel mass flow ratio equal to 0 and increasing the water to fuel mass flow ratio with a step of 0.5, an increase in RON of about 8 points was

**Fig. 2.** RON as a function of water to fuel mass flow ratio for different gasoline blends.

registered for each step water to fuel mass flow ratio increase. Imposing a water to fuel mass flow ratio of 1.5 an increase in the RON of about 25 was registered. The effect of increasing RON is due to the cooling of the end gas by the water avoiding knock. Thus, it is possible to run the engine at higher volumetric compression ratio that corresponds to a higher RON.

On the basis of the presented results (see Fig. 2), CR30 BL2 leads to a 93 RON that is the closer RON of commercial gasoline with anti-knock additives.

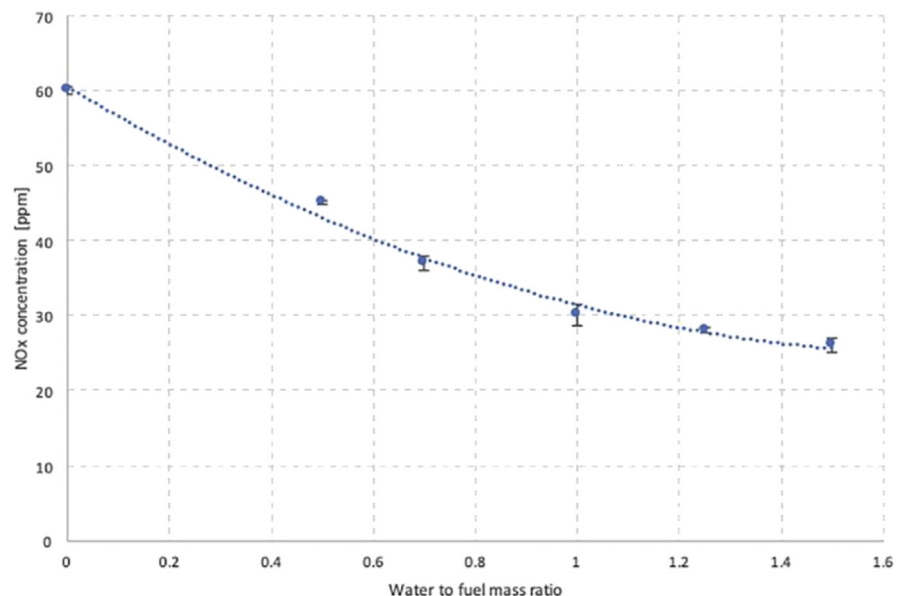
As it is evident in Fig. 2 a linear increment is obtained with each blend. It has been determined a unique mathematical expression to linearly correlate the octane number increment with the water/fuel ratio as reported in Eq. (1).

$$ON_{water} = ON_{base} + \frac{25}{1.5} w/f \quad (1)$$

where  $ON_{water}$  is the octane number obtained using water injection with a ratio  $w/f$ , starting from a base octane number  $ON_{base}$ .

Tests were performed using a reference fuel blend rated at 65 RON (Base RON 65—65 % by vol. of iso-octane and 35 % by vol. of n-heptane). The choice of this RON is strictly linked to the RON value of the virgin naphtha blend that is rated in the range 63—68 RON.

In order to evaluate the effects of water injection on nitric oxides emissions, NO<sub>x</sub> emissions were measured during the tests varying water to fuel mass rate at fixed volumetric compression ratio (see Fig. 3). NO<sub>x</sub> emissions decrease increasing the water to

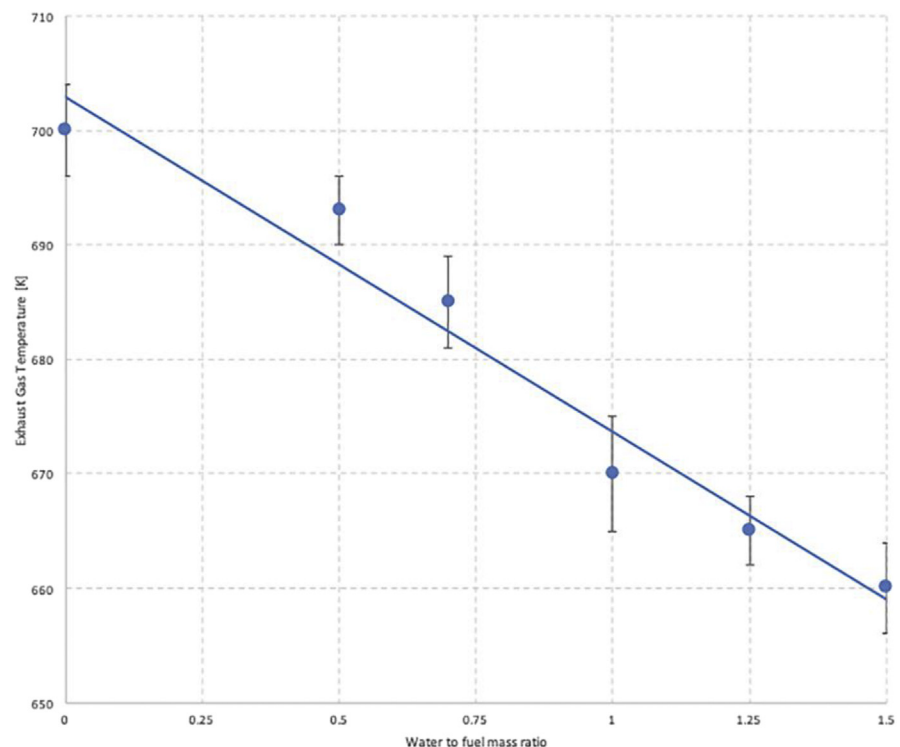


**Fig. 3.** NO<sub>x</sub> concentration versus water to fuel mass flow ratio for reference fuel blend (CR = 5.25 - Base RON 65).

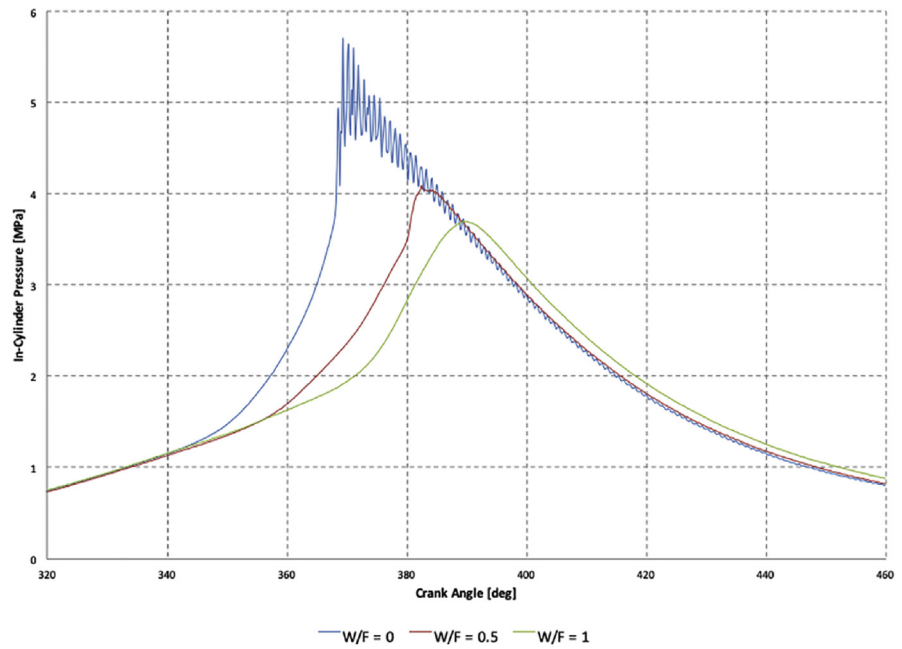
fuel mass flow rate and this is present in any case. Using a water to fuel mass flow rate of 1.5 leads to a NO<sub>x</sub> emission reduction of about of 50%. The reduction of nitric oxides is due to combustion chamber cooling by the water obtaining a lower in-cylinder mean temperature. This is also confirmed by a lower exhaust gas temperature measured downstream of the exhaust valve during engine tests (see Fig. 4). As it is evident the exhaust gas temperature decreases almost linearly with water to fuel mass flow rate with a decrease of about 6% varying the water to fuel mass flow rate from 0 to 1.5.

As far as the effects of water injection on the in-cylinder pressure it is concerned, Figs. 5 and 6 show in-cylinder pressure as a function of engine crank angle and swept cylinder volume, respectively. Different water to fuel mass flow rate are reported ( $w/f = 0, 0.5$  and  $1$ ). The CFR Fuel Engine volumetric compression ratio was set to make sure that engine knock occurred. In particular, a volumetric compression ratio of 5.25 was fixed and the engine fed with a reference fuel.

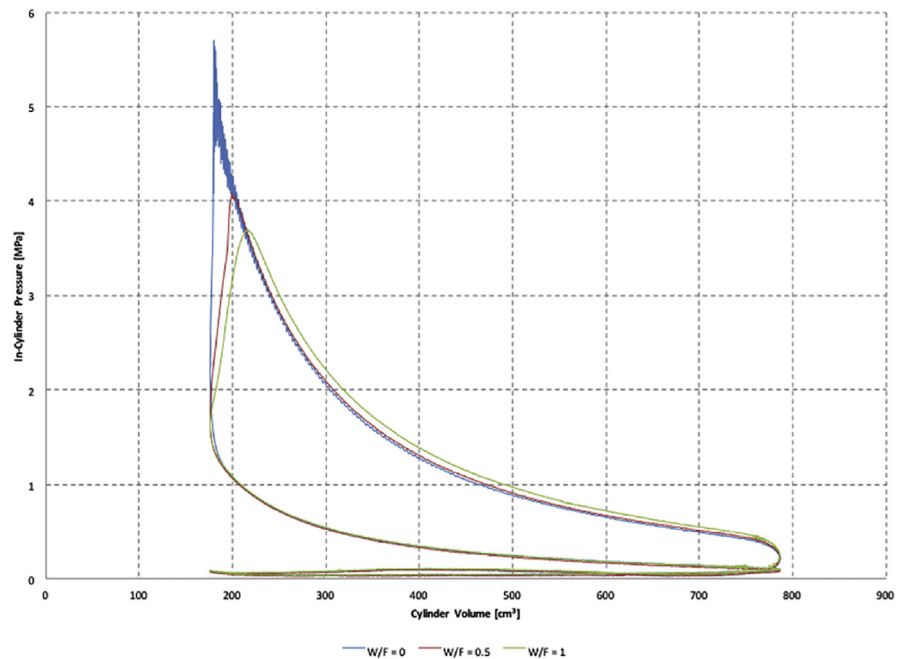
As it is possible to observe in Figs. 5 and 6, knock occurs without water injection. Using a water to fuel mass flow rate different from zero knock disappears at the same volumetric compression ratio. This confirm that water could be used to control knocking in internal combustion engines. At the same time, a delay in SOC is evident that lead to a delay in the crank at which in-cylinder pressure peak occurs. A decrease in pressure peak level of about 1–1.5 MPa is evident, as well.



**Fig. 4.** Exhaust gas temperature versus water to fuel mass flow ratio for reference fuel blend (CR = 5.25 - Base RON 65).

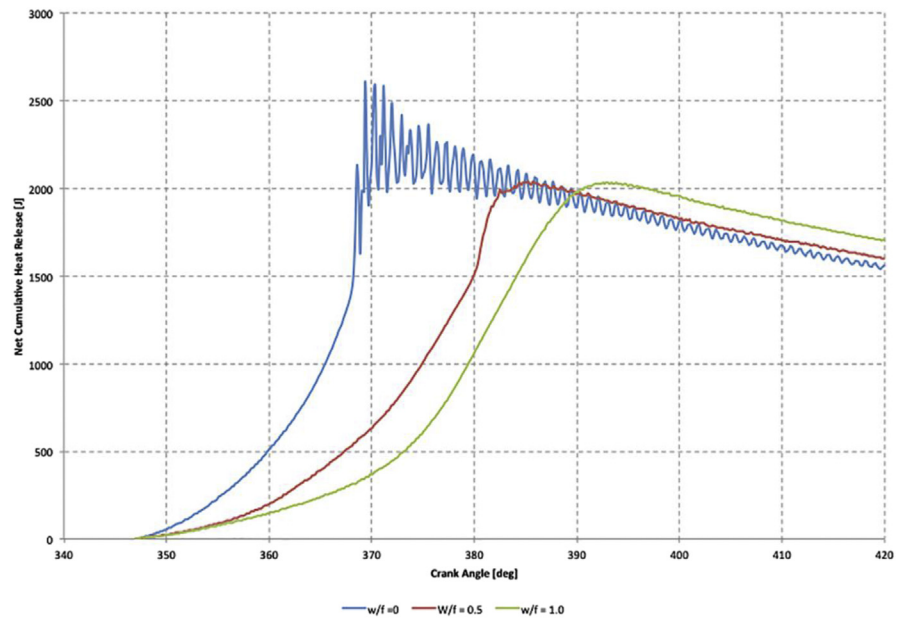


**Fig. 5.** In-cylinder pressure as a function of crank angle for different water to fuel mass flow ratios and fixed engine volumetric compression ratio (Base RON 65).



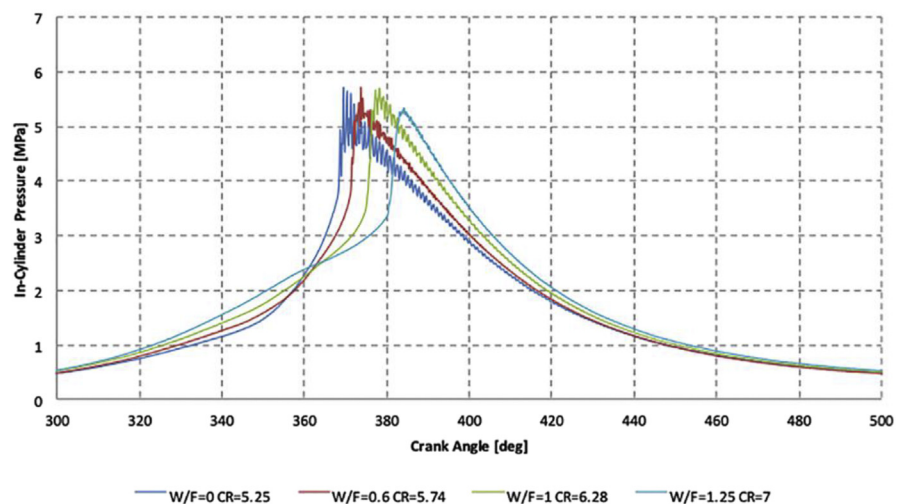
**Fig. 6.** In-cylinder pressure as a function of cylinder volume for different water to fuel mass flow ratios and fixed engine volumetric compression ratio (Base RON 65).





**Fig. 7.** Net cumulative heat release as a function of crank angle for different water to fuel mass flow ratios and fixed engine volumetric compression ratio (Base RON 65).

The effects of water injection on the heat release are shown in Fig. 7 [29]. In that figure, Net Cumulative Heat Release curves, as a function of engine crank angle, calculated using in-cylinder pressure data, for three water to fuel mass flow rate ( $w/f = 0.0$ ,  $w/f = 0.5$ ,  $w/f = 1.0$ ), are shown. It is evident that the presence of water inside the cylinder slightly reduces the heat release intensity and retard the end of combustion phase. This confirms that water introduction into the cylinder allows a regular energy release during combustion. This energy release can be transformed in active work to the piston instead of being dissipated in wall heat transfer.



**Fig. 8.** In-cylinder pressure as a function of crank angle for different water to fuel mass flow ratios and variable engine volumetric compression ratio (Base RON 65).

In order to investigate about the capability of water injection method to control knock, CFR fuel engine was fed with reference blend and a volumetric compression ratio to have knock was set (see Fig. 8 – W/F = 0 CR = 5.25 blue curve). In this case, a pressure peak of about 5 MPa was registered. Therefore, engine volumetric compression ratio and water to fuel mass flow rate were varied to maintain about the same pressure peak level. As it is possible to observe in Fig. 8, effects of water injection are evident. The same pressure level is possible with higher volumetric compression ratio. At the same time an increase of water to fuel mass flow rate is necessary. Knock intensity decreases increasing water amount as well. These facts confirm that water could be used to control knock phenomena and allow higher compression ratios.

#### 4. Conclusions

In the present paper, a study on knock and pollutant emission control method is presented. In particular, water injection was used as antiknock fluid. At the same time emission reduction was achieved.

An experimental campaign based on CFR Fuel Engine running on reference fuels with and without water injection highlighted the benefits of the proposed technique. A heat release analysis of the combustion data highlighted that a regular energy realised could be achieved using water as knock control fluid.

Based on the experimental results the main effects of the water injection could be summarized as follows:

1. water injection is an effective technique to improve anti-detonation fuel quality;
2. water injection affects in-cylinder gas temperature leading to a lower NO<sub>x</sub> emissions;
3. water injection allows to use higher volumetric compression ratios.

Moreover, water injection could also be used for obtaining high power densities coupled with boost pressure techniques for turbocharged engines. Water injection is an effective method to reduce the turbocharger engine knock inclination.

#### Declarations

#### Author contribution statement

Sebastian Brusca: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Stefano Mauro, Michele Messina: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Antonio Galvagno, Rosario Lanzafame: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

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## Competing interest statement

The authors declare no conflict of interest.

## Additional information

No additional information is available for this paper.

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