Investigation of water injection for hydrogen combustion phasing control on a boosted spark ignition single cylinder research engine

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ABSTRACT

This paper investigates the use of water injection as a means to enable safe operation of hydrogen spark ignition engines near stoichiometric conditions. The study focuses on mitigating knock phenomena and improving combustion phasing in high-load operating conditions. Experimental tests were conducted on a single-cylinder research engine, and parameters were measured and analyzed. The results show that lower excess air ratios allow for higher achieved loads and reduced spark timing requirements for optimum combustion phasing. However, knock occurrence becomes a challenge at higher loads and closer to stoichiometric conditions. Water injection was employed to mitigate knock, and its effects on combustion-related parameters and engine performance were examined. The findings reveal that water injection increases combustion duration and delays ignition timing. The injected water mass flow rate and spark timing were found to be crucial factors in achieving knock-free operation and maintaining engine efficiency. Although water injection slightly reduces engine load, it improves indicated efficiency. This research demonstrates the potential of water injection as a strategy for enhancing the performance and safety of hydrogen spark ignition engines at near stoichiometric conditions.

INTRODUCTION

The high reactivity of hydrogen enables its combustion to occur much more easily than other fuels, such as ethanol or gasoline. This condition allows for the operation of an internal combustion engine in a lean mode, meaning with an air-to-fuel ratio significantly higher than stoichiometric, in a stable manner, with air-fuel equivalence ratios (λ) close to 5. On the other hand, operating under stoichiometric conditions presents two main difficulties: due to its high reactivity, H2 has a tendency to undergo autoignition, which occurs frequently if the ignition timing is not sufficiently retarded, despite hydrogen having a research octane number (RON) above 130 [1]. Additionally, hydrogen consumption is higher than that of conventional fuels like gasoline due to its low energy density per unit volume - 8 MJ/dm³ compared to gasoline's 32 MJ/dm³, even when liquid hydrogen is considered [2]. It is evident from the above that the advantage of operating with hydrogen lies in the ability to maintain stable operation with a higher excess of air compared to conventional fuels, which brings the benefit of fuel economy.

Extreme boosting strategies are required to achieve high engine loads at high excess air ratios. A requirement of 2.0 bar intake pressure enabled only 12 bar BMEP at an excess air ratio of 2.2 to enable knock free operation [3]. This is a low load value compared to modern downsized flex-fuel engines. Thus, to achieve higher engine loads, at some point, boosting pressure becomes a limiting factor, and near-stoichiometric operation becomes necessary. However, at higher loads and with an air-fuel ratio closer to stoichiometric, the tendencies for abnormal combustion with hydrogen occur more frequently, thus preventing efficiency gains under these conditions. Therefore, there is a desire to explore increasing the load with air-fuel ratios as close to stoichiometric as possible without experiencing detonation effects. To achieve this, the use of water injection brings benefits in reducing the reactivity of the air-fuel mixture at the expense of a decrease in volumetric efficiency.

Regarding previous studies on water injection combined with hydrogen engine operation, it was observed that water is capable of reducing NOx emissions formed during combustion due to the temperature reduction inside the cylinder. On the other hand, water also contributes to the reduction of the volumetric efficiency of the engine [4]. Water injection into the intake manifold was studied in a dual-fuel hydrogen and gasoline engine, where, besides the reduction in NOx emissions, a decrease in Brake Specific Fuel Consumption (BSFC) of up to 4.61% was evident [5].

The water injection solution can be implemented without significant architectural modifications compared to current platforms, using commercially available components such as high or low-pressure solenoid injectors [6-7]. Additionally, the increase in the thermal capacity of the charge also aids in reducing the temperature at the end of compression. As a result, the temperature of the unburned gases is reduced compared to combustion without water addition, allowing for optimal ignition timings to be used in high-load operating conditions [8-9]. This leads to increased operational efficiency and the possibility of increased torque at maximum load [10]. To eliminate the need for water replenishment from the fuel injection system and avoid potential shortages, several authors have studied the feasibility of using recycled water from dew-cooled exhaust gases [7], [11-13]. This fact is particularly relevant in the case of hydrogen engines, given the large amount of water generated by its combustion in the form of vapor, which, when condensed, can serve as a source for injection water. Water injection would also have the collateral benefit of reducing combustion temperature and lowering NOx emissions.

This study investigated the use of water injection as a resource to enable safe hydrogen spark ignition engine operation near stoichiometric conditions. An excess of air ratio sweep study was performed to evaluate the excess air ratio at which knock borderline occurs at CA50 of maximum indicated efficiency. At this excess air-ratio, the effect of water injection on knock mitigation was studied.

METHODOLOGY

EXPERIMENTAL SETUP – The experimental tests were conducted on a single-cylinder spark ignition internal combustion research engine, the Ricardo Proteus. This engine has a displacement volume of 1172.6 cm³, a compression ratio of 10.1:1, a bow-shaped combustion chamber, and an overhead valvetrain system. For this particular configuration, a fuel injection system with four solenoid injectors injecting H2 into the intake runner was used, along with a single water injector installed in the intake port. A supercharger compressor was used to achieve 1.5 bar of intake pressure. Both gas and liquid mass flow measurements were taken using two Coriolis effect instruments. All combustion parameters were derived from the signal of an in-cylinder piezoelectric pressure sensor GH14D, which measured the instantaneous pressure of the combustion chamber gas. The indicated data was acquired with a resolution of 0.1 degree of crank angle using a 3600 pulses per revolution encoder. The experimental setup is illustrated in Figure 1.

TEST PROCEDURE – Initially, tests were carried out to investigate the knock occurrence at a constant intake pressure of 1.5 bar during boost operation, with the aim of determining the λ value of border knock. The relative air-to-fuel ratio was varied with values of λ=2.2, λ=1.8, and λ=1.3, until knock occurrence started to appear on the in-cylinder pressure signal. A backpressure valve was used to maintain a constant -0.35 bar of PMEP. The same test was then conducted at a constant intake pressure of 1.0 bar during wide-open throttle naturally aspirated operation. The same λ values were varied to compare knock occurrence conditions. As λ was increased for both intake conditions, the load was also increased until it reached the knock limit. To investigate the impact on load and efficiency in this region, the spark timing was adjusted between -4°, -6°, -8°, and -10° ATDCf for each λ value.

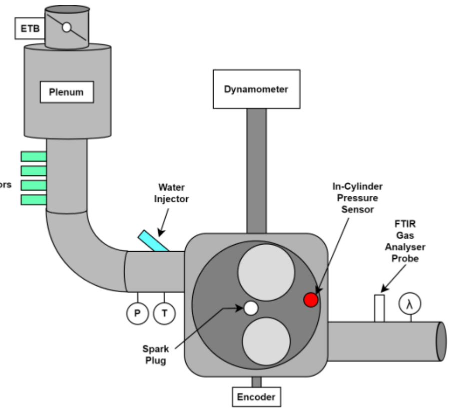

Figure 1. Experimental engine setup.

Later, water injection was used in 0.5 ms injection pulse width steps increments (lower injection pulse width that guaranteed injector opening and stable water supply) to mitigate the knock phenomenon for each test condition at λ=1.3, where knock started to happen. For each spark timing tested, water injection quantity was varied until knock was fully mitigated.

The main parameter chosen as knock index was SEPO (signal energy of pressure oscillations) calculated as (1) [14]. Knock phenomenon was considered to happen for SEPO values higher than 10 bar².deg for individual cycles of the 100 cycles data acquisition package. If some of these cycles presented values around 10 bar².deg, that was considered border knock operation. Additionally, knock free operation was considered when no individual cycle presented values higher than 10 bar².deg.

$$SEPO = \int_{\theta_0}^{\theta_0+\Delta\theta} {P_{filt}}^2 d\theta \qquad (1)$$

RESULTS

LAMBDA SWEEP AT CONSTANT INTAKE PRESSURE - In this study, the impact of varying intake pressures (1.0 and 1.5 bar) on the occurrence of knock during operation at the optimal spark timing for maximum efficiency was investigated. Figure 2 (a) demonstrates that lower excess air ratios resulted in higher achieved loads and reduced spark timing requirements for attaining optimum combustion phasing (Figure 2 (b)). Additionally, significant reductions in flame development angle (CA0-10) and the duration of the main combustion phase (CA-10-90) were observed (Figure 2 (c)). Knock-free operation persisted until an intake pressure of 1.3, at which point the knock index (KI), evaluated as SEPO, began to rise while attempting to maintain optimal combustion phasing.

It was also determined that the sweet spot for efficiency in this engine, at its specific compression ratio, resided between 3.0 and 1.8 λ, achieving a maximum load around 5 bar IMEP, significantly lower than that observed in naturally aspirated non-hydrogen-fueled engines. This phenomenon can be attributed to the lower volumetric density of hydrogen.

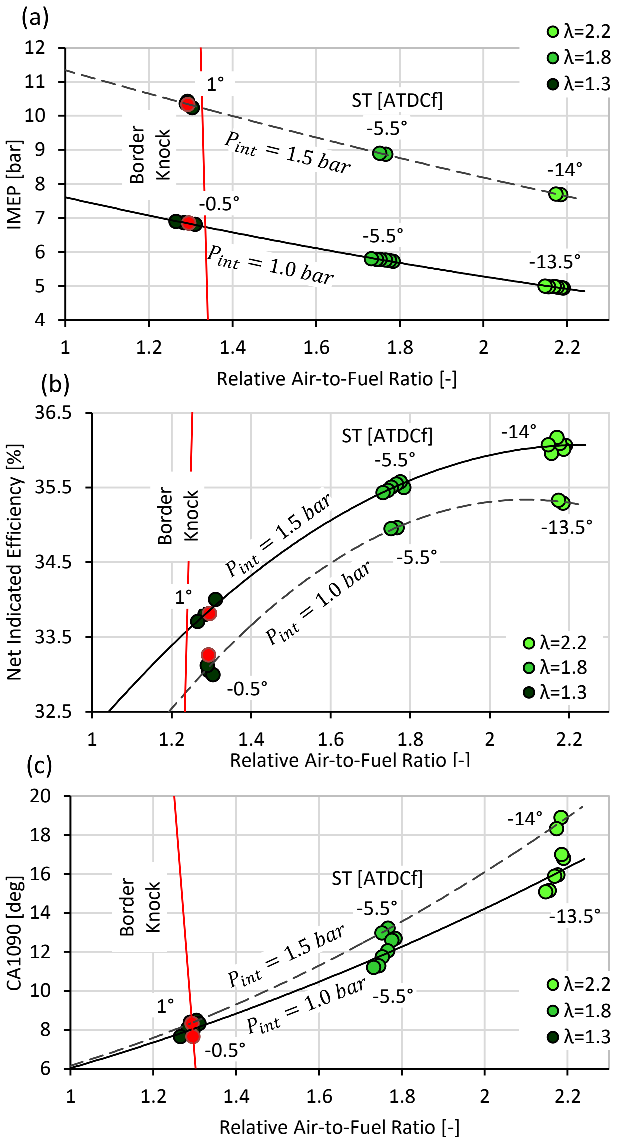

Figure 2. Experimental engine setup.

HYDROGEN KNOCK MITIGATION USING WATER INJECTION - During wide-open throttle (WOT) operation at an intake air-fuel equivalence ratio of 1.3, CA50 values lower than approximately 8 CAD ATDCf proved unattainable due to the prevalence of severe knock events. Figure 3 presents CA50 achieved for several spark timings. At the spark timing of -4 CAD ATDC, the 100 cycles mean KI value indicated heavy knock occurrence. When investigating the individual cycle KI, it can be seen that many cycles achieved values higher than 10. At this point, the water injection procedure started. As several injection pulse widths were used for each tested spark timing, only three cases were chosen to be shown here, as show in Figure 3 (a): red indicates the lowest water injection quantity possible to operate under heavy knock condition where individual cycle SEPO values achieved more than 10 bar²deg (Figure 3 (b)); pink indicates the lowest water injection quantity to promote border knock operation when some cycles achieved maximum SEPO values of 10 bar².deg (Figure 3 (c)); blue indicates the lowest water injection quantity to enable knock free operation when no individual SEPO values achieve 10 bar²deg (Figure 3 (d)).

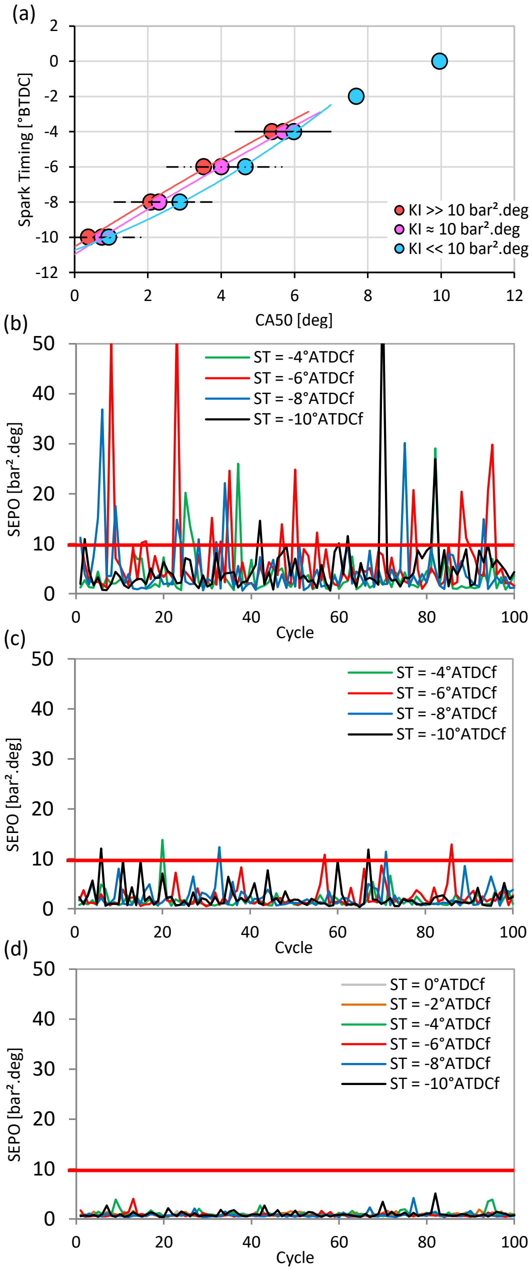

Figure 3 - (a) Spark timing requirement to achieve CA50 values for water injection quantities that resulted in knock (KI>10 bar²deg) , knock borderline (KI~=10 bar²deg), and knock free (KI<10 bar²deg) engine operation. Individual cycle SEPO values for (b) knock (KI>10 bar²deg), (c)

knock borderline (KI~=10 bar²deg), and (d) knock free (KI<10 bar²deg) engine operation.

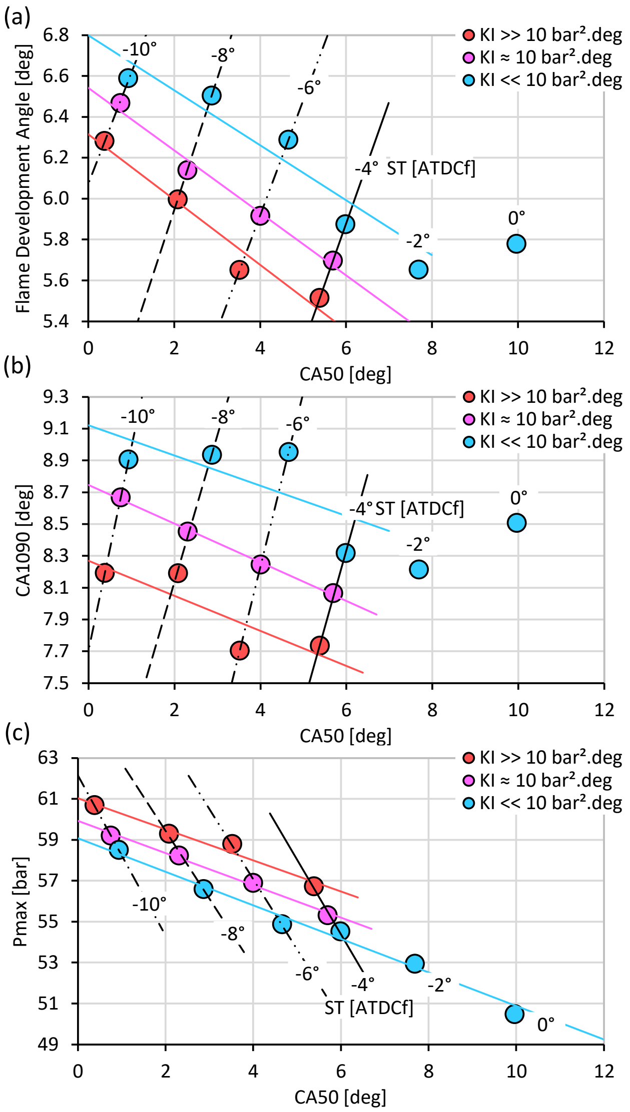

Figure 4 – (a) Flame development angle (CA0-10) by variation of by multiple spark timing and injected water; (b) Combustion duration (CA10-90); (c) Maximum cylinder pressure (Pmax).

WATER INJECTION EFFECTS ON COMBUSTION RELATED PARAMETERS - Figure 4 (a) and Figure 4 (b) presents combustion duration as a function of CA50 for several spark timings. It is important to highlight that for the knocking cycles, as spark timing was advanced, higher water mass flow rates were necessary to maintain operation within acceptable knocking levels. Thus, flame development angle (CA0-10) increased as spark timing was advanced, contradicting the intuitive expectation for operating conditions without water injection and knock. Similarly, the main phase of combustion (CA10-90) also increased for more advanced spark timings. Both combustion duration parameters were affected by the water mass injected, and durations increased with water addition. As combustion duration increased, CA50 and the angle of maximum pressure were delayed when water was added while comparing the same spark timing condition. Longer combustion durations also explain the reason why maximum pressure was reduced when more water was added for constant spark timing Figure 4 (c).

Regarding engine operation stability, higher water injection increased both CA0-10 and CA10-90, leading to increased combustion variability and resulting in higher COVimep values for cases with higher water injected mass. The dilution effect of water injection is also observed on exhaust temperature. Since water has a considerably higher heat capacity than air, water addition reduced in-cylinder temperatures and exhaust gas temperature, even for the later end of combustion.

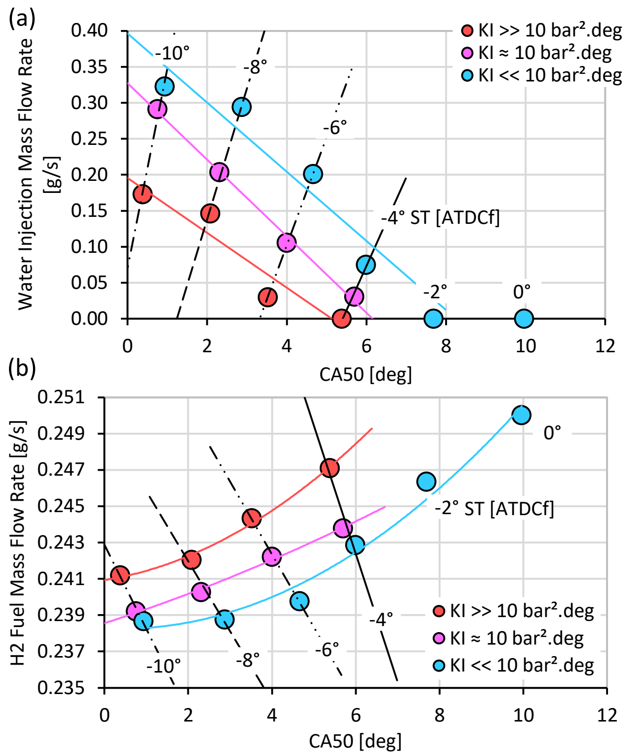

Figure 5 – (a) Water mass flow rate variation by spark timing and effect on knock occurrence; (b) Hydrogen fuel mass flow rate by spark timing and water injected to control knock occurrence.

WATER INJECTION EFFECT ON ENGINE PERFORMANCE - This section presents the results of water injection's effect on the engine operation performance parameters at WOT condition (constant intake pressure of 100 kPa) and λ=1.30. Figure 5 (a) and Figure 5 (b) present the required water mass flow rate to achieve knocking conditions and the injected H2 mass flow rate, respectively. As the test proceeded at a constant intake pressure, the added water mass in the intake port reduced the oxygen partial pressure. Thus, while water was added, the mixture was enriched and λ was reduced. This could be monitored by the oxygen sensor in the exhaust manifold, and it required a reduction of injected H2 mass to maintain λ at 1.30+-0.01. A direct consequence of lower energy input to the engine was the load reduction (Figure 6 (a)). Thus, the higher the mass of water injected, the lower the load.

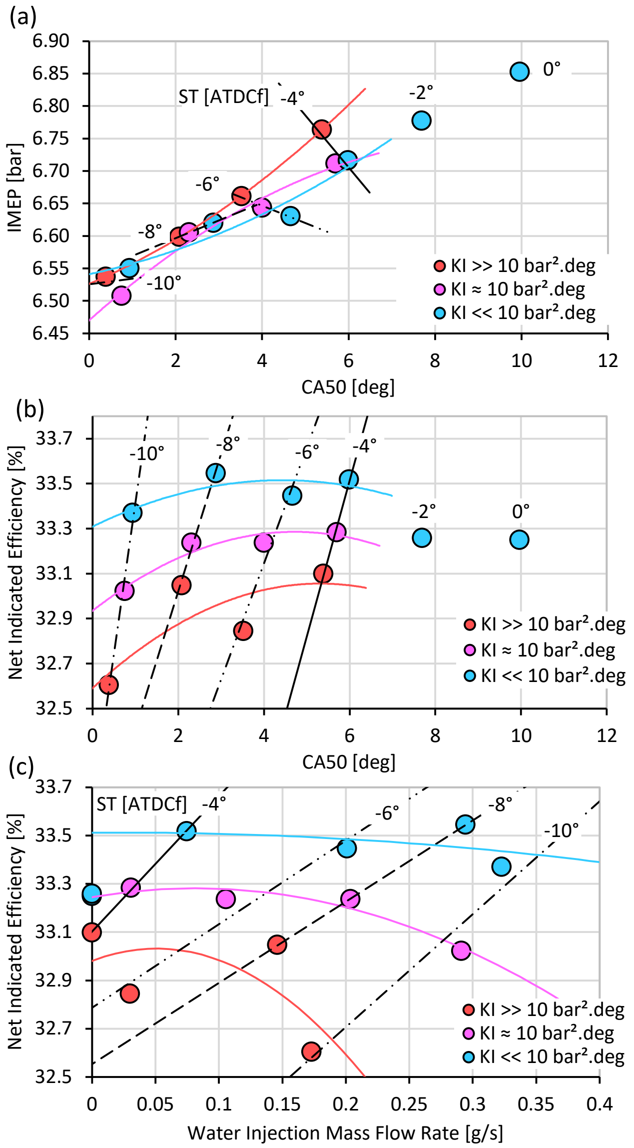

Figure 6 – (a) Indicated Mean Effective Pressure (IMEP) decreasing by addition of water and spark timing advance; (b) Combustion phasing for optimum net indicated efficiency; (c) Net indicated efficiency increasing with water injection.

On the other hand, water addition promoted higher engine efficiency at each spark timing tested (Figure 6 (b)). However, there was a compromise between efficiency, spark timing and water injection (Figure 6 (c)). As spark timing was advanced, more water was required to enable acceptable knock levels for KI>10 bar²̇.deg.

Finally, NOx emissions were reduced when using water injection. This is explained by the temperature reduction caused by dilution. The Zeldovich NOx formation mechanism illustrates that high temperature and N2 and O2 concentrations directly affect NO formation. Thus, water injection both reduced combustion temperatures and reduced N2 and O2 concentrations.

CONCLUSION

Water injection was investigated as a resource to promote safe SI engine operation when operating with hydrogen at near-stoichiometric conditions to attain high load operation with lower boosting requirements. As presented in the literature, it was found that water addition reduced engine volumetric efficiency at constant intake pressure. For a constant excess air ratio, the use of water to mitigate knock slightly reduced engine load but increased indicated efficiency. Depending on spark advance and knocking tendency, higher water injection quantity was required to mitigate knock. However, as a general trend, water injection had always increased engine operation efficiency for constant spark timings while considerably reducing NOx emissions.

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