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In Application

Evaluation of Water Injection Strategies for NOx Reduction and Charge Cooling in SI Engines

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Introduction

Water injection is a promising technology for further improving fuel efficiency, reducing emissions and increasing power in internal combustion engines. Especially in spark ignition engines reaching higher efficiencies is limited by knock. Charge cooling by water injection has been shown to effectively mitigate knock. In addition, water injection can lead to reduced NOx emissions.

An experimental study to evaluate different water injection strategies was carried out at the Chair of Powertrain Technologies at the Technical University of Berlin[1]. LaVision's Internal Combustion Optical Sensor (**ICOS-Temperature**) was used to measures crank angle resolved in-cylinder water concentration and temperature. Using this information, a better evaluation of the different water injection strategies was possible.

Experimental Setup

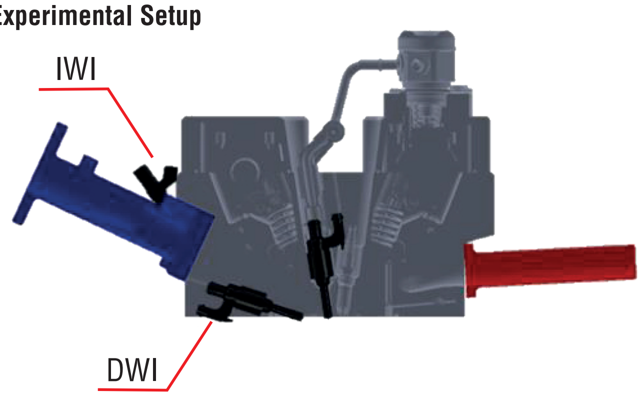

Figure 1: *Cylinder head showing indirect water injector (IWI) and direct water injector (DWI)[1].*

A single cylinder engine was equipped with indirect water injection (IWI) in the intake manifold and in-cylinder direct water injection (DWI) as shown in Figure 1. An **ICOS-Temperature** system with an integrated spark plug probe was used for water concentration and temperature measurements.

Water Mixing

Figure 2 shows the complex mixture formation with direct water injection in comparison to the more homogenous mixture with indirect water injection in the intake manifold. For IWI the effect of injection timing (SOI) is marginal. For DWI the effect of injeciton timing is clearly visble during mixture formation and the water concentration just before ignition varies considerably.

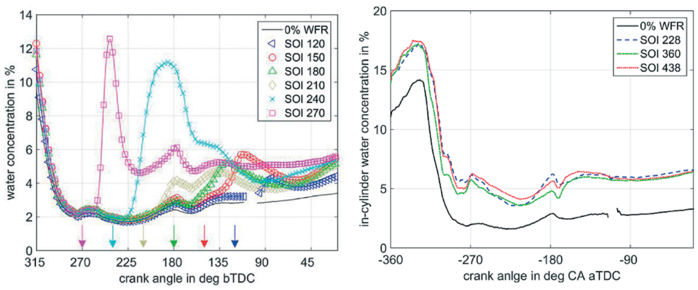

Figure 2: *Water concentration during mixture formation for DWI (left) and IWI (right). Individual plots represent different water start of injection (SOI) timings. 0% water fuel ratio (WFR) is plotted for reference[1].*

Water Cooling Efficiency

The amount of water for reducing the charge temperature and thus mitigating knock should be kept to a minimum. In order to easily evaluate a water efficiency number was introduced. This parameter relates the actual charge cooling achieved to the maximum potential that could have been achieved for a given amount of water. The efficiency of the cooling tends to decrease with increasing amounts of water (Figure 3). Direct water injection is more effective for lower water amounts. For higher water fuel ratios both IWI and DWI show similar efficiencies.

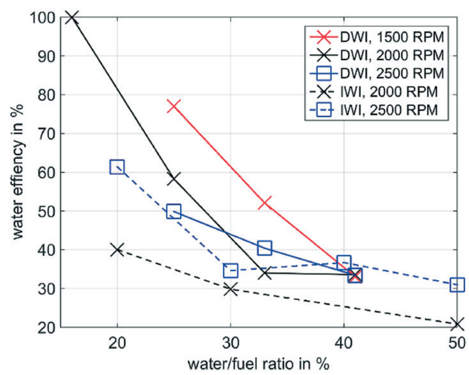

Figure 3: *Water efficiency number for IWI and DWI for different water amounts, plotted as water/fuel ratios[1].*

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Water Efficiency Loss

One important factor for cooling efficiency of water injections is the actual amount of water which contributes to the combustion process. Figure 4 shows the water concentration just prior to ignition plotted over the water/fuel ratio. While the IWI shows a linear relationship between injected water and amount of water present at the end of compression, the DWI clearly shows lower pre-ignition water concentrations for the same amount of injected water. This indicates increased water loss during DWI for higher water/fuel ratios. Especially for DWI, the injection timing is is critical (Figure 2) because water can accumulate near the cylinder walls or even impinge on the cylinder liner and potentially contaminate the engine oil. In both cases the amount of water contributing to the reaction will be reduced leading to a loss in the water efficiency.

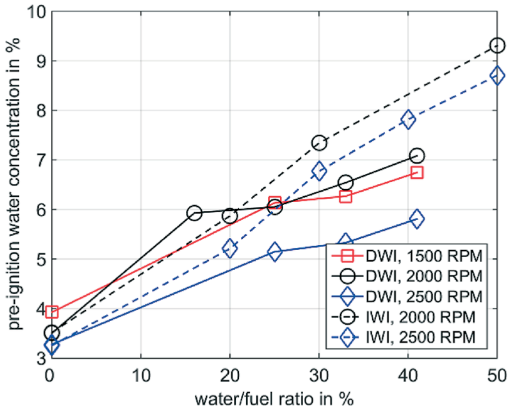

***Figure 4:** Pre-ignition water concentration for DWI and IWI for injected water/fuel ratio[1].*

NOx Reduction

Charge cooling not only mitigates knock but also has a positive effect on some engine-out emissions, particularly NOx. Figure 5 shows the NOx reduction. While maximum values of up to 60% reduction were achieved with IWI, only about 40% could be achieved with DWI. This can be explained by the reduced amount of water contributing to the reaction during direct injection, DWI. When plotting NOx reduction against the measured water concentration (Figure 6) instead of the nominal injection water/fuel ratio (Figure 5), it can be seen that there is a clear relationship between the amount of water contributing to the reaction and the NOx reduction.

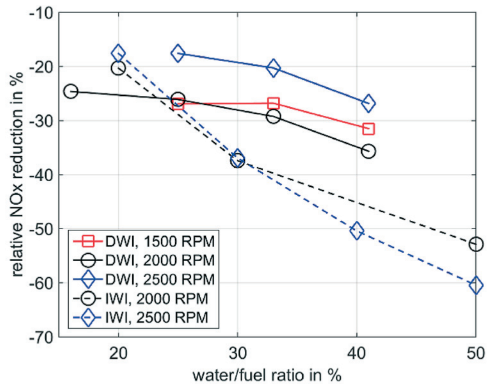

***Figure 5:** NOx reduction due to water injection plotted against injected water/fuel ratio[1].*

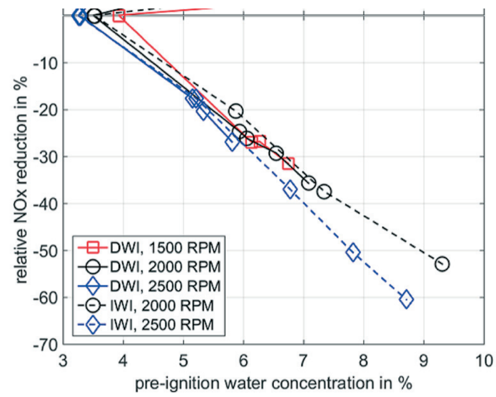

***Figure 6:** NOx reduction due to water injection plotted against injected actual pre-ignition water concentration at the spark plug[1].*

Summary

Cooling effciencies showed little difference between DWI and IWI for higher water/fuel ratios. But IWI was more effective in reducing NOx. By measuring the in-cylinder water concentration it was possible to determine the water loss and thus find an explanation for the less effective NOx reduction for DWI.

Reference

[1] M. Kauf, M. Gern and S. Seefeldt, "Evaluation of Water Injection Strategies for NOx Reduction and Charge Cooling in SI Engines", JSAE 20199014, SAE 2019-01-2164.

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