

Water Injection as an Enabler for Increased Efficiency at High-Load in a Direct Injected, Boosted, SI Engine

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ABSTRACT

In a Spark-Ignited engine, there will come a point, as load is increased, where the unburned air-fuel mixture undergoes auto-ignition (knock). The onset of knock represents the upper limit of engine output, and limits the extent of engine downsizing / boosting that can be implemented for a given application. Although effective at mitigating knock, requiring high octane fuel is not an option for most markets. Retarding spark timing can extend the high load limit incrementally, but is still bounded by limits for exhaust gas temperature, and spark retard results in a notable loss of efficiency. Likewise, enriching the air-fuel mixture also decreases efficiency, and has profound negative impacts on engine out emissions. In this current work, a Direct-Injected, Boosted, Spark-Ignited engine with Variable Valve Timing was tested under steady state high load operation. Comparisons were made among three fuels; an 87 AKI, a 91 AKI, and a 110 AKI off-road only race fuel. The engine was outfitted with a sequential port water injection apparatus. Under full-load, water injection enabled operation with 87 AKI fuel at near optimal combustion phasing, and with a stoichiometric air-fuel ratio. This resulted in up to a 5% improvement in Net Mean Effective Pressure and up to a 34% improvement in thermal efficiency compared to the production ECU Calibration. A detailed comparison on combustion phasing, burn rate, Mean Effective Pressure, water requirement, and efficiency is presented in this paper.

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INTRODUCTION

Background

Engine downsizing is a method of increasing vehicle fuel economy that has been used for decades. The basic premise of downsizing is to size the engine such that the road loads of the typical drive cycle for the vehicle application are not heavily throttled as is the case with a large displacement engine. This effectively decreases pumping losses and increases efficiency on the drive cycle. However, if Naturally Aspirated (NA), the acceleration and gradeability of the vehicle are limited by the downsized displacement.

The decrease in engine output is compensated for, and in many cases surpassed, by boosting, most commonly with a turbocharger. The boosting system / turbocharger increases the Volumetric Efficiency (VE) (as referenced to ambient conditions) at Wide Open Throttle (WOT), thereby increasing the dynamic range of the engine.

Unfortunately increasing engine output via boost is not entirely unbounded. As the boost level increases, so does the propensity for knock (autoignition). Operating in an autoignition regime can lead to catastrophic engine failure, and thus forms the upper bound for boost levels and engine output.

The knock limit can be deterred, albeit incrementally, through several means, all with their drawbacks. Decreasing Compression Ratio (CR) has a detrimental impact on engine efficiency throughout the entire operating range, including the drive cycle and light load operation. Increasing the Octane Number (ON) of the fuel adds a price premium. Some consumer markets may not support the increased fuel cost, and even so, there is an upper limit on the ON that can be practically achieved. Switching to a high ON fuel such as Natural Gas brings other potential issues. Decreasing inlet air temperature has packaging and cost challenges, and still has limitations. Retarding Spark Advance (SA) decreases efficiency while leading to increased Exhaust Gas Temperature (EGT) which can bring with it a plethora of durability concerns. Furthermore, there is a point of diminishing returns where further increases in boost are merely counteracted by the decrease in efficiency resulting from the spark retard. Fuel enrichment decreases efficiency and increases engine out exhaust emissions in the operating zone where it is used.

Another alternative for knock mitigation is injection of water into the Air / Fuel mixture, either upstream of the inlet valve, or directly in-cylinder. The concept of water injection is not new. Researchers studied water injection on piston aircraft engines at least as early as the late 1930's and through the 1940's [1, 2]. Additional work

continued [3, 4, 5, 6, 7]. Water injection is experiencing renewed interest now [8, 9] with the increasing emphasis on highly boosted downsized engines [10].

Water is effective at sequestering knock through multiple mechanisms. With a latent heat of vaporization of 2257 kJ/kg [11] water has the effect of substantially cooling the charge air as the liquid water vaporizes. Furthermore the water vapor acts as a diluent in the combustion process, sequestering knock reactions in much the same way as cooled Exhaust Gas Recirculation (EGR) gas.

Motivation

Evidence suggests that even at the degree of downsizing common with many production engines today, real-world fuel consumption is actually worse than it would be with a conventionally sized engine [10]. The reasons for this are likely 1) excessive spark retard to control knock, and 2) excessive fuel enrichment also to limit knock, and to limit high EGT resulting from the spark retard. Both spark retard and fuel enrichment have a detrimental impact on engine efficiency. Furthermore, without a paradigm shift, the current trend in downsizing and boosting will reach a plateau, where additional increases in boost pressure are simply not practical with any level of spark retard and fuel enrichment due to knock and pre-ignition limitations.

A study is being conducted to investigate benefits of water injection in boosted engine applications. The objectives are:

1. Quantify the potential for water injection to improve high-load / full-load efficiency at boost levels that are typical of current production highly boosted engines
2. Quantify the potential for water injection as an enabler for ultra-high boost, including boost levels beyond current production maximum boost, as well as boost levels beyond what is attainable with current pump grade fuels.

This paper will report on results focused on objective 1. The paper will describe the experimental test bed, the variables and test plan, present and discuss results, and finally draw conclusions from this phase of the project work.

EXPERIMENTAL SETUP

Base Engine

The engine platform chosen for this work is the General Motors Ecotec, specifically RPO code LHU. This is a Spark-Ignited, 2.0L 4-cylinder engine with a turbocharger, Direct Injection (DI) of fuel, and Dual Independent Variable Valve Timing (DIVVT). This platform was selected for several reasons:

- The technology level (DI, Turbocharged, DIVVT) is representative of most other highly boosted production engines,
- At 25 bar BMEP [12], the production brake output is at the upper most end of current production engines [10]. This suggests the platform has sufficient hardware strength for testing at least across the load spectrum for current production engines,

and implies it is a suitable starting point for increasing load beyond current production levels.

- Availability of production level parts through an extensive network of OEM dealers and aftermarket automotive parts retailers.
- This platform has a strong following in the motorsports industry, and therefore, there exists a wide selection of racing components intended to provide additional strength in high load operating conditions.

Two test engines have been prepared. With the exception of instrumentation, and the addition of a water injection system, one engine remained in an entirely production configuration. This engine was used to 1) calibrate and validate the control system, water injection system and other aspects of the test bed and 2) investigate the impact of water injection up to current production boost levels. Specifically this engine is being used to meet Objective 1 stated previously. Additional details on this engine are shown in [Table 1](#).

Table 1. Details of the Engine Testbed.

Engine Specifications		
Base Engine	Configuration	Inline 4-Cylinder, Pent-Roof Central Spark Plug
	Displacement	1998 cc
	Bore	86.0 mm
	Stroke	86.0 mm
	CR	9.2:1
	Valvetrain	4-Valve / Cyl, DIVVT
	Fuel System	Direct Injection (Wall Guided)
	Induction	Twin Scroll Turbocharged

For the testing with water, an apparatus was designed and fabricated to separate oil and water from the blow-by gas. This allowed for assessment of the amount of water moving through the crankcase. The production PCV system was utilized for the tests without water injection.

The second engine is being used to meet Objective 2, and thus is being utilized at boost levels significantly higher than current production. As such, this engine has been assembled with aftermarket and fabricated components as required to 1) reach output levels significantly higher than current production, and 2) maintain durability when operating at these high load conditions. Additional details on this testbed and results obtained from it will be forthcoming in a future publication.

INSTRUMENTATION

Testing was done with an AC dynamometer operating at steady state. Combustion analysis was completed with an A&D CAS system, AVL GH15D pressure transducers and BEI 360X encoder. The pressure

transducers were mounted with a 1 mm X 3 mm passage to the combustion chamber. The 360X encoder was interpolated in the CAS software to provide a sampling rate that exceeded the Nyquist criteria for knock frequency at 2000 RPM. Exhaust temperature was measured at the turbine outlet, turbine inlet, and each exhaust runner ~70mm downstream of the exhaust valves. The details on the major instrumentation are shown in Table 2.

Table 2. Instrumentation details.

Instrumentation Specification	
Dynamometer	350 kW AC
Combustion	A&D CAS, AVL GH15D Pressure Transducers, BEI Optical Encoder
Flow	Air: Meriam Laminar Flow Element Fuel: Emerson Micro Motion Coriolis Meter Water: Emerson Micro Motion Coriolis Meter
Exhaust	Bosch LSU4.9 wideband lambda sensors
General	Omega Gauge & Absolute Pressures, Temprel Type K Thermocouples, National Instruments PXI Electronic Data Acquisition and test cell control

The engine setup is shown in Figure 1.

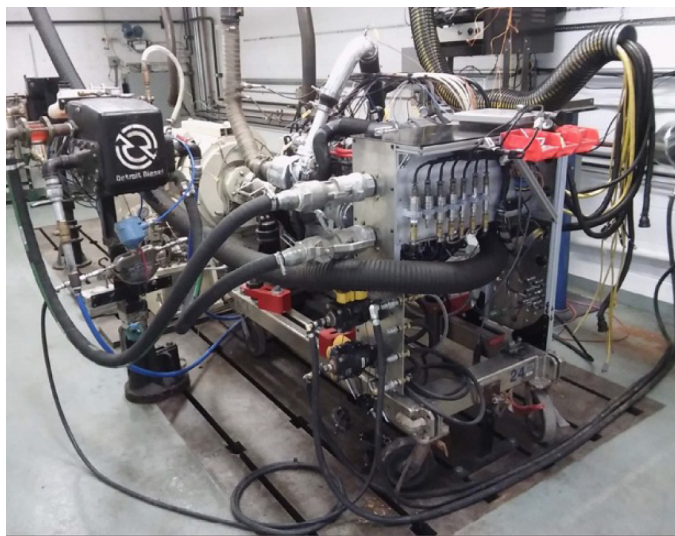


Figure 1. Engine setup in the testcell.

Water Supply System

The water supply system includes a Reverse Osmosis water filtration system, holding tank, pressurization to either Port Injection (PI) or DI requirements, and flow and pressure metering. Test water is prepared on-site with a Reverse Osmosis (RO) water filtration system. The purified water reduces variability and unknown effects that might otherwise be caused from salts, minerals, and other chemicals in the water supply. The water moves directly from the RO system to a 150 L holding tank.

The high pressure system (for DI) draws water directly from the holding tank and utilizes a pneumatic piston driven pressure booster to send water to a floating piston, Nitrogen pressurized accumulator, then through a high-pressure coriolis meter and to the engine.

For PI, water is gravity fed to a 45 L pressure vessel. The 45 L pressure vessel can be pressurized with standard process air (~860 kPa). For this testing the air pressure transferred the water through the same high pressure Coriolis meter then to the engine. Since this testing, the system has been updated with a low pressure Coriolis meter for the low pressure PI system. The low pressure Coriolis meter has a larger internal diameter, and imposes less pressure drop than the high pressure meter.

Manual 2-way and 3-way valves are used configure the water supply system for either DI or PI operation. Up to the engine, all fittings and lines are stainless steel to eliminate corrosion potential. A detailed schematic of the water supply system is shown in Figure 2.

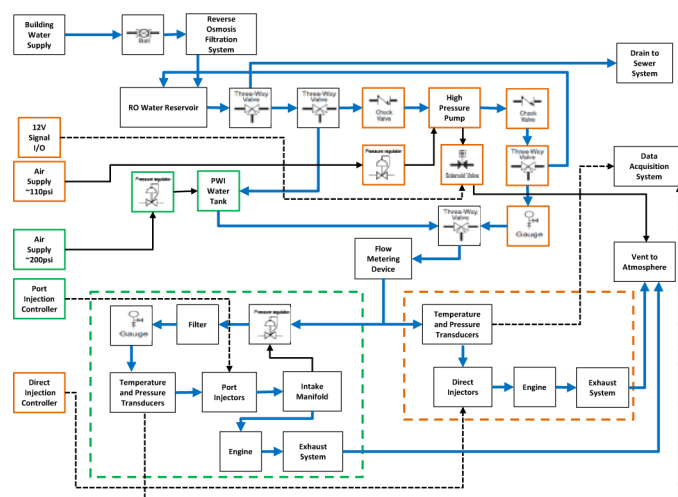


Figure 2. Details of the water supply system.

Water Injection

As noted previously, the water supply system has been fabricated to provide pressure capable of supporting either direct, or port injection. Thus far, all water injection testing has been done through PI, and those details will be described here.

A production Bosch EV14 PI fuel injector has been installed in each of the 4 intake runners. A mounting boss and water rail was designed and fabricated. The mounting boss was fabricated from aluminum, and welded to the aluminum intake manifold. The mounting boss was designed to provide a fastening point for the water rail, which in turn retained the injector. The injector was targeted such that the center of the spray is centered in the intake port, just upstream of the septum.

An additional regulator that is referenced to intake manifold pressure is mounted to the engine, and provides the final adjustment of the water pressure. The details of the engine mounted water injection system are shown in Figure 3 and 4.