EXPERIMENTAL INVESTIGATION ON THE EFFECT OF INJECTING WATER TO THE AIR TO FUEL MIXTURE IN A SPARK IGNITION ENGINE

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Water injection is a means of internal cooling of the engine. During combustion, excess temperatures generated are absorbed by water as latent heat. Optimum water injection quantities were found to be about 0.015 ml to 0.031 ml of water per cycle on a 592 cc SI engine. The experiments were carried out by tapping the fuel injector signal and designing a circuit to inject water at the instant petrol is injected. Fuel injection duration was tuned by using a Wide Band Lambda sensor. The engine was supercharged as well by means of compressed air supply and regulated by hysteresis control. Water injection was investigated while varying spark advance to find the Maximum Brake Torque (MBT). Maximum obtained torque improvement with water injection was 16 %. This was achieved at a manifold absolute pressure of 120 kPa, with air temperature at ambient. The same load condition, 120 kPa, with air heated to the temperature that would be obtained from isentropic compression, resulted in a torque improvement of 7 %.

KEYWORDS
thermal engineering, ignition internal combustion engines, mechatronics, automotive applications, water injection

1. INTRODUCTION

The internal combustion engine has been used extensively in the last century for various applications. These include aircraft, electrical generators, automobiles and multipurpose industrial engines. Aircraft engines require less weight with remarkable power. Cooling procedures to reduce pre-detonation in the combustion chamber was studied extensively. The goal of these studies was to allow more charge into the cylinder so as to capture more power from the engine.

Water injection at the intake dates back to the 1930's, where engine manufacturers needed to find some type of knock suppression for aircraft engines at high power. The problem of knock forced engine manufacturers to reduce the compression ratio of the engine to suppress in cylinder pressures. Reduction in the compression ratio meant compromising thermal efficiency. Water injection at the intake, provided a means of cooling due to the high latent heat of vaporization of the water. Conquering the knock suppression problem allowed the use of superchargers at high altitudes for aircraft engines.

Supercharging an engine is a means of extracting more power from the engine. Higher pressures at the intake allow more air and fuel mixture to flow into the engine cylinder. More mixture in the cylinder leads to a better volumetric efficiency and higher torque developed by the engine. Supercharging obviously increases the pressures and temperatures during combustion and measures for efficient cooling and knock suppression should be correctly taken.

This paper describes an investigation of water injection at the intake port of a spark ignition internal combustion engine. The setup consisted of a single cylinder engine with electronic port fuel injection. The fuel injection was controlled via an Electronic Control Unit (ECU). The ECU allows more control on the engine by providing the capability of changing several engine parameters during operation. These parameters included fuel mapping for stoichiometry and spark advance for maximum torque. The water injector was physically set up next to the petrol injector at the intake port. Such an investigation also required a means to control the quantity of water injected and supercharging the engine to study the effect of water injection at elevated intake pressures.

2. LITERATURE REVIEW

Water Injection has been in use in aircraft engines as a means of internal cooling from the early 20th century. This internal cooling can provide space or means for additional charge to be allowed in the cylinder for more power output without the danger of premature detonation of the charge inside the cylinder. A mixture of methanol with water is frequently used so that water does not freeze at high altitudes. Such mixture was known as Antidetonant Fuel Injection or ADI. Such studies were important for the early era of flight engines as, due to weight issues, getting the maximum power from an engine was a huge benefit instead of just increasing the capacity of the engine. Water Injection as a means to suppress knock at very high engine power and speeds was a very feasible way instead of adding antiknock compounds to the fuel [Wild 2003]. In the analysis of water injection to reduce gasoline consumption, Engelman and White [Engelman 1944], discussed how water can be efficiently injected to the intake manifold to act as an internal coolant instead of making the air-to-fuel mixture rich so that extra fuel will act as a lubricant and cooling fluid as well. Their experiment was carried out at wide open throttle. Temperature limited comparisons were taken using only rich air-to-fuel ratios and water injected stoichiometric mixture. When either fuel mixture was enriched or water was added, the throttle was opened to reach the same temperature at normal operation. Engelman and White showed that for the same temperature limit, water injection allowed more power to be extracted from the engine in terms of brake horse power. Up to 900 b.h.p., power outputs are the same, however fuel cooling was stopped due to knocking at around 1040 b.h.p. Temperature limited power using water allowed up to 1180 b.h.p. with the added benefit of lower fuel consumption. In another scientific paper, Lanzafame [Lanzafame 1999] discussed how water can be used effectively both as an internal coolant, and moreover to suppress knock. Such conclusion can also be made from the analysis above of Engelman and White, where fuel cooling was stopped due to knock, while water cooling allowed more power without detonation. Lanzafame also noted that water injection reduced NOx emissions by more than 50% with water-to-fuel mixtures of about 1.5 at the intake. The author discussed that the possible reason for knock suppression with water was due to the fact that the latter slowed combustion. Since knocking can be caused due to the very fast heat release during combustion at high power, slowing it down will also reduce the risk of premature detonation [Lanzafame 1999]. He also discussed that water injection is much more effective in supercharged or turbocharged engines since the water injected would vaporize during the compression stroke, so that the cooling effect will allow more air and thus more power. In naturally aspirated conditions, water vaporization will commence during combustion [Lanzafame 1999]. From the findings of Lanzafame, the in-cylinder pressures shows that knocking was suppressed with the use of water injection. The exhaust temperatures were also reduced considerably. The effects of the temperature of water injected directly into a SI engine on engine efficiency, stability and emissions were studied by Le-Zhong Fu et al. Le-Zhong found that engine indicated work and thermal efficiency increased with water injection. The increase of the temperature of water being injected resulted in higher peak in-cylinder pressure and improves MEP. The improvements were bigger at higher engine loads [Fu 2014].

An interesting investigation by Brun, Olsen and Miller [Brun 1944] is the water injection in a localised spot where the premature detonation is most likely to occur, that of the further end of the frame front. By using the NACA high speed camera, at a rate of 40,000 frames per second, they concluded that the knock reaction involved only a small fraction of the cylinder/piston area. This is a localised spot, where the unburned mixture is continuously pushed outward of the flame direction where it is confined by the cylinder walls, and therefore its volume is decreased. This volume decrease increases the temperature and pressure of the end-gases, after which knock will occur [Brun 1944]. The authors suggested that effective reduction in antiknock additives and refined gasoline could be eliminated by injecting smaller amounts of additives particularly at this zone, defined as the 'end-zone' by the authors. The authors used three spark plugs to propagate the flame to a particular zone and they have put the water injector at the end zone. The violent knock produced without water injection was damped by the use of water injection. Water injection also maintained uniform pressure in the cylinder and reduced the effect of losing power due to knock. The amount of water injected was 1.3 times that of fuel. The authors discuss how this value was the best value to suppress knock, and due to experimental setup limitations, they could not go lower than 1.3 times, to prove better knock suppressing. The angle at which the water should be injected in similar situations is very critical [Brun 1944].

A thesis by Leonard C Nelson [Nelson 1949] studying the effect of water injection in a spark ignition engine with different fuel grades states that no effect of water on power or s.f.c. was seen. These tests were all done in a naturally aspirated engine and the spark advance was varied as well, in contrast to other authors' work. Regarding spark advance, water injection in this particular publication allowed the spark to be advanced without knocking in contrast to that of no water injection [Nelson 1949]. The author favours the system of water injection for its cooling properties and the advantage of using water instead of tetra-ethyl lead, the latter being very pollutant to the environment and to human health. The author describes that tetra-ethyl lead reacts with the mixture of fuel to change its self-ignition temperature. On the other hand, the water cools the in-cylinder temperature so that the self-ignition temperature is not reached [Nelson 1949]. This conclusion matches the conclusion of Rowe and Ladd who studied the behaviour of water, water-methanol and water-ethyl injection in aircraft engines. Their conclusion was, that water is a very good and effective knock suppressor and internal coolant, where the addition of methanol increases the power output of the engine. Water-ethyl injection is inferior to both scenarios mentioned above [Rowe 1945]. A similar study by Vandeman and Henicke was conducted using water-methanol mixture of 0.2 and 0.4 coolant to fuel ratio. The authors concluded that water only did not contribute to power output as much as water-alcohol injection as also stated by Rowe and Ladd [Vandeman 1945].

Water injection is also an effective way to reduce NOx emissions. As discussed earlier, Lanzafame [Lanzafame 1999] reports NOx dropped by 50% when water was injected. In another scientific paper by D M Hollabaugh [Hollabaugh 1966], he discussed that NOx formation is a function of peak in-cylinder temperatures during combustion and fuel to air mixture that is the more oxygen is available, the better for NOx formation. Reduction of NOx by enriching the mixture is an alternative, but it is a waste of fuel while emissions of hydrocarbons and carbon monoxide will also increase as a result. The best NOx reduction was with a water injection ratio of 1.1, where the reduction was 84.5%. Even with alcohol-water injection with a 20/80% solution, NOx reduced significantly. However there was an increase in hydrocarbons.

3. EXPERIMENTAL SETUP

A single cylinder JAP Model 6, side valve, air cooled engine connected to a dynamometer was used for water injection testing at the University of Malta. The engine general data is compiled in Table 1. The engine was configured to port fuel injection by Camilleri [Camilleri 2013]. Camilleri's setup included a water injector at a 45° incline with the intake pipe as shown in Figure 1. The engine was controlled with an Electronic Control Unit (ECU) by Reata Engineering®. Electronic enhancement of the setup was implemented on various subsystems as discussed in [Busuttil 2014b].

Engine Characteristic	Value
Bore	85.90mm ±0.05mm
Stroke	102.25mm ±0.05mm
Cubic Capacity	592.50cc ±0.75cc
Compression Ratio	4.97
Magneto Spark Ignition	20.00° BTDC
Inlet Valve Open	17.00° BTDC
Inlet Valve Closes	52.00° ABDC
Exhaust Valve Open	48.00° BBDC
Exhaust Valve Closes	9.00° ATDC
Inlet Valve Maximum Lift	7.00mm
Exhaust Valve Maximum Lift	7.23mm
Inlet Valve Inner Seat Diameter	31.70mm±0.05mm
Inlet Valve Outer Seat Diameter	35.60mm±0.05mm
Exhaust Valve Inner Seat Diameter	31.45mm±0.05mm
Exhaust Valve Outer Seat Diameter	35.45mm±0.05mm

Table 1. General Engine Characteristics

Figure 1. Modified Intake Pipe with Fuel and Water Injectors

A Wideband Lambda Sensor, a Powderx AFX Monitor was installed to measure the AFR. The sensor allowed the alteration of the fuel injection duration to make the air to fuel ratio close to stoichiometric during testing. It was also beneficial to analyze the effect of water on the combustion and power with regards to air to fuel ratio.

The JAP engine was originally equipped with a magneto ignition system. Ignition with the magneto occurs only at 20° Before Top Dead Centre. This method is very convenient for normal operation in the industry. However a variable spark timing system was needed to run tests to find the Maximum Brake Torque of the engine at different Manifold Absolute Pressures (MAP) loadings and various water injection levels. The conversion was made with the use of an ignition coil and setting up the correct timing from the ECU to pull the ignition circuitry to ground. The system was set up to energize the coil 8 ms before the spark needs to be initiated. These 8 *ms* are necessary because the ignition coil has its own inductance and current takes some amount of time to saturate and maintain maximum magnetic flux in the coil. The ECU then controls at which point the spark is generated according to the spark advance timing inputted in the Graphical User Interface (GUI) [Farrugia 2012]. The spark timing was set up using a stroboscope and checked against timing marks on the flywheel. The stroboscope light was also aimed at the side valves to check that ignition was on closed valves, *i.e.* the side valves were stationery at the firing instant which meant that that cycle was in the power stroke.

3.1 Water Injection Setup

Water was provided to the injector as illustrated in Figure 2. Compressed air was directed to a pressure regulator set at 4 bar. Water was pressurized with this air and the injector at the intake pipe was

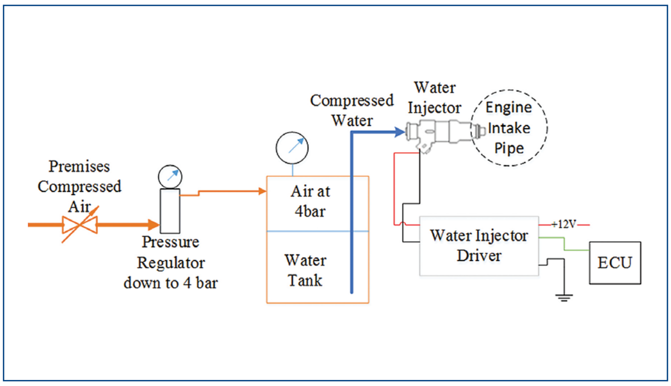

Figure 2. Schematic of the Water Injection System

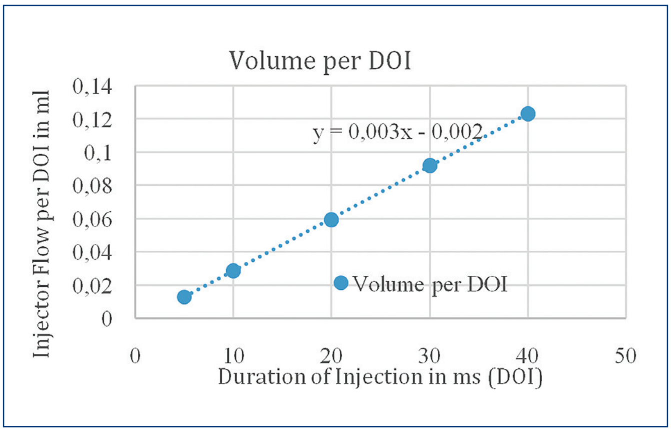

Figure 3. Water Injection Flow

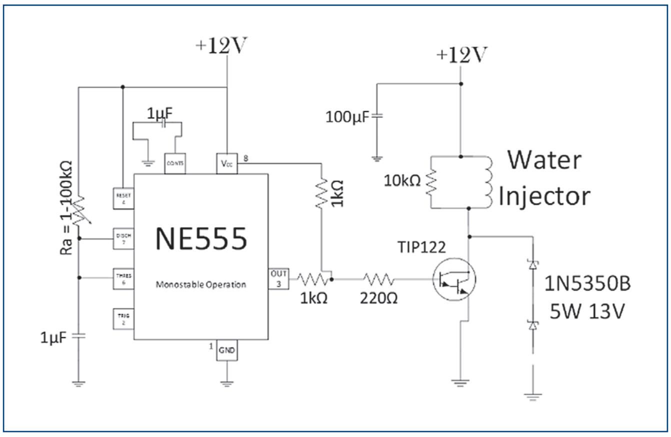

Figure 4. Water Injection Controller Schematic

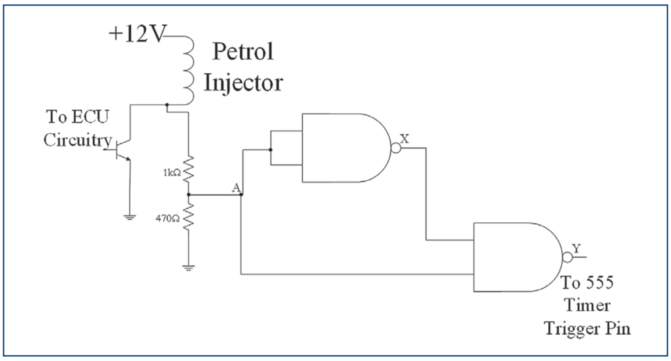

Figure 5. Trigger Generator for 555 Timer

connected to the pressurized water. The pressure at which the water is pressurized affects the flow rate of the injector once opened. An injector flow test was carried out and resulted that the injector flows at a rate of 0.0031 ml/ms with a dead time of 0.87 ms as shown in Figure 3. The dead time of an injector is the time required for the inductor of the injector to successfully pull and subsequently also allow the return spring to close the pintle of the injector. The injector therefore cannot be operated below the dead time. The injector was controlled with a water injector driver designed particularly for this study. The driver was interfaced with the ECU as detailed later.

A 555 Timer was used to control the duration of water injection. The 555 Timer was used in the Monostable configuration. In this configuration, as soon as the trigger of the 555 Timer momentarily goes to LOW, the 555 Timer outputs a HIGH pulse. The pulse width depends on the charging time constant of a Resistance Capacitor (RC) (Equation 1) circuit connected to the Integrated Circuit (IC) chip [Floyd 2006]. When the trigger of a 555 Timer goes momentarily low, a capacitor starts charging up. As soon as the voltage in the capacitor reaches 0.6667 of the supply voltage of the IC a comparator turns on a discharge transistor. The capacitor is discharged to ground through this transistor in the IC chip of the 555 Timer. A schematic of the circuit is illustrated in Figure 4.

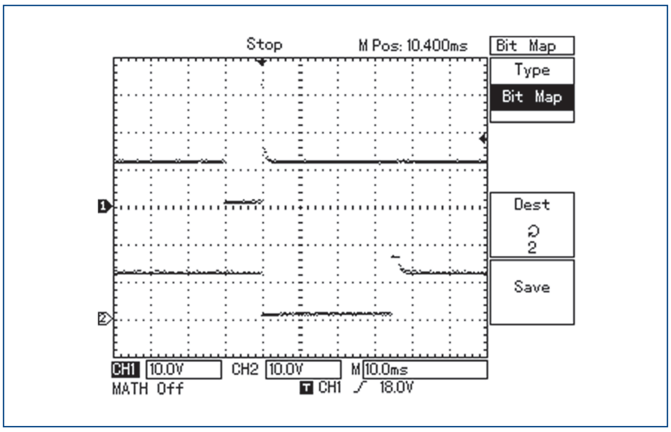

Figure 6. Oscilloscope screenshot of the system triggered at 18V

The trigger of the 555 Timer is triggered by an external circuit connected to the petrol injector of the engine. Two NAND gates are used as an edge finder of the petrol injector pulse. Propagation Delay (PD) of a logic gate is the time the logic gate takes for the output to occur after an input has been initialized or changed [Floyd 2006]. This property is used to find the instant the petrol injector is closed. At the instant the injector is switched on in Figure 5, input A is pulled to ground. As soon as the injector closes, a flyback voltage spike is created up to 33 V (the zener diode voltage rating within the ECU injector driver). This is a HIGH to input A. However, due to propagation delay, the output is momentarily changed to LOW because the output of NAND Gate 1 is retarded by this delay time. This triggers the 555 Timer.

The 555 Timer varies the pulse width by means of a variable resistor in the RC circuit. From the data sheet [Texas Instruments] of the 555 Timer, a 1 µF capacitor with a variable resistance from 1 to 100 kΩ varies the pulse width from 1 *ms* to 0.1 *s*. Equation (1) represents the relationship of this pulse width duration. The variable resistor was replaced by a dual potentiometer, one side connected to the 555 Timer circuit, and the other side was connected to a 5V, ground and signal to the ECU. The signal in the ECU was calibrated against oscilloscope readings since the pulse width duration was linear as in Equation 1. ECU then logged the duration of injection of water continuously.

$$t_{PW} = 1.1RC \tag{1}$$

Figure 6 is an oscilloscope screenshot showing the petrol injector signal in the upper trace and the water injector signal in the lower trace. As the petrol injector is switched OFF, *i.e.* the positive going edge, the water injector is triggered ON by the 555 Timer in the lower trace, i.e. the voltage trace goes through a negative going edge.

3.2 Supercharging Control

Supercharging the engine was achieved by using a control solenoid valve from the laboratory compressed air supply. The control valve was appropriately chosen for sufficient mass flow rate. A hysteresis controller was programmed in C Language using LabVIEW® to open or close the valve according to the limits specified and MAP loading at the intake. The ON/OFF controller opens and closes the solenoid valve and consequently causes the pressure in the intake plenum to oscillate between the maximum and minimum limits. The feedback sensor used was a MAP Sensor at the intake plenum of the engine. Figure 7 illustrates the control system.

A National Instruments 6009 USB module was utilized and LabVIEW was used to read the pressure and provide controller output. The output voltage from the controller was only a 5V signal. A circuit to drive the solenoid valve from the controller output signal was designed to drive the 12V solenoid valve coil. A power transistor was used to pull the solenoid valve to ground when the controller output sends a 5V signal.

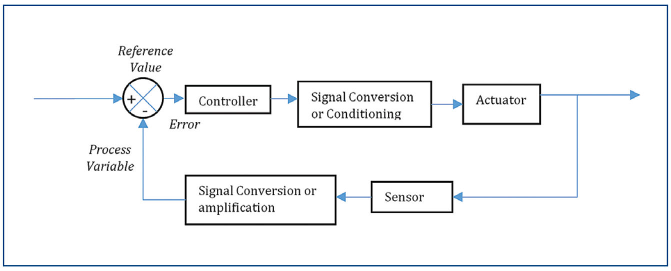

Figure 7. Supercharging Closed Loop Control Schematic

3.3 Load Cell Amplifier and Calibration

The load cell signals were connected to the non-inverting input of two operational amplifiers with closed loop feedback. The advantage of a closed loop with feedback op-amp configuration as opposed to the open loop, is that the voltage gain can be reduced. Therefore the op-amp can work in a range which is linear and within 5 V. The 5 V being the maximum recognized input signal to the ECU. An open loop configuration has a very high gain and the output can be non-linear [Floyd 2005]. An LM358 IC chip was used as shown schematically in the circuit in Figure 8. The LM7809 is a voltage regulator of 9 V. Each op-amp IC chip varies from one another and the electrical characteristics in the input impedance of the chip of each op-amp affect the output of the whole load cell amplifier. Theoretically, connecting the differential inputs of the op-amp to ground and powering, the output should read zero volts. However, practically this is not the case and an offset voltage appears. Therefore a 10 kΩ potentiometer was connected to the inverting signal to offset this voltage between the inputs [Floyd 2005]. To null this voltage an experiment was carried out to check at which load the amplifier starts to output a voltage with the wiper of the potentiometer set at 0*k*Ω [Floyd 2005]. The experiment was carried out using an oscilloscope. With no-load on the load cell the offset null voltage pot wiper was turned until a voltage reading of around 0.6 V was measured at the output. This way the amplifier gave a signal as soon as a load is applied to the torque arm. The load cell was then calibrated with actual masses and converted to torque. The calibration was inputted into the ECU to log data.

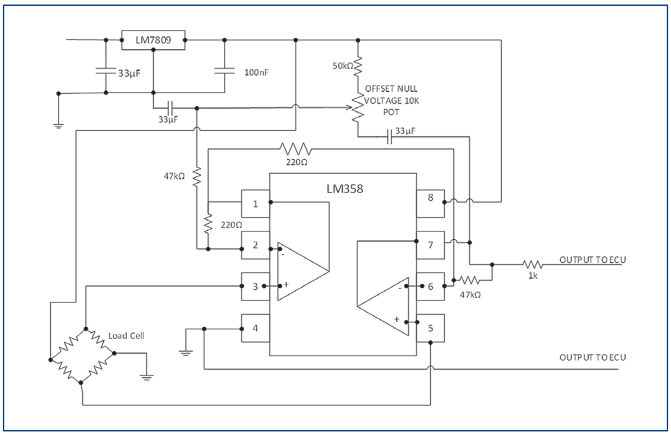

Figure 8. Load Cell Amplifier Circuit

4. TESTING RESULTS AND ANALYSIS

Engine experiments were performed to determine the water injection effects on performance as well as determine the effects water injection has on the spark timing for MBT and fuel quantity required for close to stoichiometry. The sub-systems described in Chapter 3 were connected as a whole system as shown in Figure 9. Experimental runs were carried out using this system. In Figure 10 an increase of 16 % in torque is noticeable from a fuel to water injection ratio by volume of 4.65. At *1600 rpm* with charge air at ambient temperature but at elevated pressure of 120*kPa* all fuel to water mixtures gave improved engine performance. At engine speeds of 1800 *rpm* and 2000 *rpm*, the effect on performance with Water Injection was minimal. The spark advance was stopped as soon as knocking sound was heard. In all engine speeds with air at ambient temperature, water injection did not allow spark advance to go beyond cases where there was no water injection. Water did not suppress knock at 120 kPa loading. This might be the result from the fact that water could have vaporized immediately as it entered the combustion chamber or during the compression stroke.

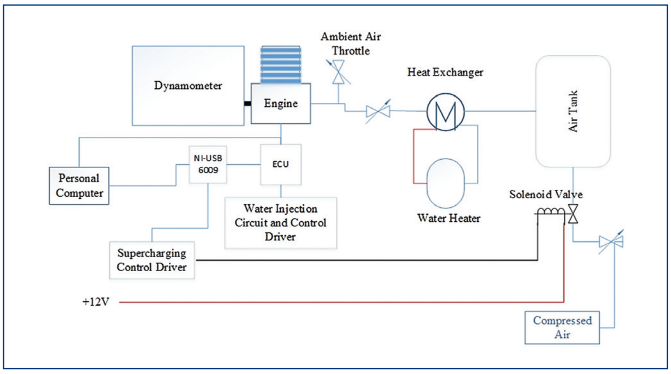

Figure 9. Experimental Setup Schematic

On the contrary to what occurred when air at the intake was at ambient temperature, the effect of water injection on charge air heated to the temperature it would reach if it were compressed isentropically, allowed more spark advance to take place at all engine speeds. Figure 11 shows the spark advance effect on torque for an engine speed of 1 600rpm, 120*kPa* and heated air. For fuel to water ratio of 4.65, the maximum spark advance was nearly 42° for knock to occur as compared to a spark advance of 32° for no water injection. Fuel to water ratios lower than 0.77 resulted in abnormal and rough operation of the engine. This is clearly shown in Figure 11 where a very low torque was measured for the 0.77 fuel to water ratio and knock occurred at 15° spark advance. At engine speed of 1600 *rpm*, a fuel to water ratio of approximately 4.6 allowed for 3 Nm increase in torque and maintained this torque evenly at very early spark advance. At engine speeds of 1 800 and 2 000 rpm respectively, the MBT was not effected by water injection.

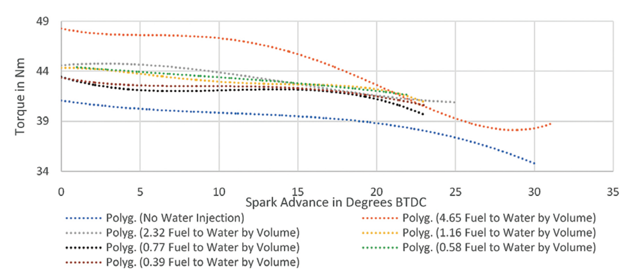

Figure 10. Torque in Nm vs Spark Advance in Degrees BTDC at 1600 rpm and 120 kPa – Air at ambient temperature

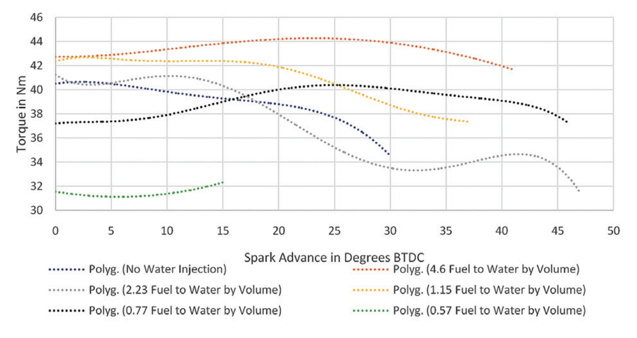

Figure 11. Torque in Nm vs Spark Advance in Degrees BTDC at 1600 rpm and 120 kPa (Heated Air)

Tests were carried out at an AFR of a bit less than 14.7 when initiating the test with no water injection. If internal cooling in fact took place, and the density of air was increased, more air would have found itself inside the cylinder making the mixture leaner. More air means more combustible oxygen. The excess fuel from a lower AFR of 14.7 can be used to utilize this air when at this scenario. This is a beneficial scenario of water injection. The Wideband values of the Air to Fuel Ratio were corrected to the AFR when water injection was introduced. Equation 2 represents the Duration of Injection for the combustion to be at stoichiometry, and when the engine was mapped for stoichiometric DOIs. The Wideband Sensor was logged at each water injection duration test and the effect on fuel requirement was determined. Equation 2 was used to correct these effects. Every injection during engine run time with water injection was corrected to an air to fuel ratio (AFR) of 14.7 [Heywood 1989] and the corresponding injection duration to achieve this AFR.

$$DOI_{stoich} = \frac{AFR_{with\ water\ injection}}{AFR_{no\ water\ injection}} \times DOI_{ECU} \qquad (2)$$

Figure 12 shows the Corrected Fuel Duration against the Water Duration. Curves plotted are the cases where the water injection was most influential on torque. Here it is noted that increase in power is due to more fuel allowed to be used as shown in Figure 12 on the blue plot. For no water injection, 16.8ms of fuel were required, while for 5ms of water injected, approximately 19ms of fuel were required. The internal cooling effect by the injected water is noticed here because the drop in temperature is what caused the higher densities of air. These effects could be further fortified by the direct measurement of air flow at the intake (Mass Air Flow – MAF) and a thermocouple to measure the intake temperature and also the Exhaust Gas Temperature.

Water injection for manifold absolute pressure of 120 *kPa* and temperature at ambient was much more effective on torque than when air is heated at the intake. This means that water injection with a charge air cooler is more effective than water injection alone as a means of intercooling. However water injection at 1 600 *rpm* 120 *kPa* with heated air still showed an improvement over no water injection with a 7 % increase in torque.

Other water injection durations at 80 *kPa* and WOT (approximately 100 *kPa)* disturbed engine performance at all engine speeds. This ineffectiveness could be explained by the effect Lanzafame [Lanzafame 1999] noticed with water injection, i.e. that water injection slows down the combustion process. This could lead to the combustion process delayed to a point where the piston was further down in the power stroke. Eventually, this delay could be reducing the effective positive work to the piston.

At supercharged operation, engine speeds of 1 800 and 2 000 *rpm* were not much effected by water injection. Water injection durations higher than 20 *ms* caused a loss in engine performance. Such disturbance could be due to loss in mass air flow rate because of high amounts of water injected. It is noted that the JAP engine used is a slow speed engine and its performance peeks at approximately 1 600 to 1 800 *rpm* for no water injection.

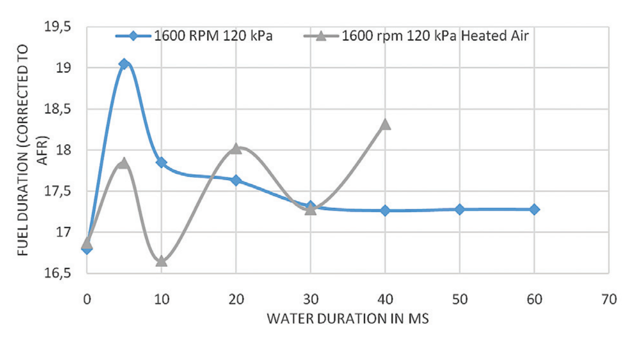

Figure 12. Corrected Fuel Duration

Another factor contributing to these inefficiencies in water injection is the compression ratio and the octane number of the fuel used. The compression ratio used for these tests was approximately 5. The engine used is a relatively old design. In the past anti-knock additives to boost octane numbers were lead alkyls. Heywood [Heywood 1989] states that these agents were at a lower expense than modifying the hydrocarbon composition by any refining process. These lead alkyls were introduced in 1923. However this additive was becoming less used in the 1970 due to its toxic nature and also due to the damage they cause to catalytic devices for emission control. Other methods to increase the octane number of fuels were the use of oxygenates in the fuel. Oxygenates are oxygen containing organic compounds. Dabelstein et al [Dabelstein 2007] stated that when manufacturers tried to increase the compression ratio of the engines, abnormal combustion took place and the gasoline formulation was to blame. Intensive study started with this regard refinery conversion processes took place to improve the octane number of fuels.

5. CONCLUSION

The investigation analysis showed that water injection was very affective at intake pressures higher than naturally aspirated. It was also noted that as expected at the higher pressure condition, torque was higher at a temperature equal to ambient rather than heated. A temperature at ambient is difficult to achieve after isentropic compression from a supercharger. To achieve such temperature a charge cooler is needed. At 120*kPa* water injection provided an increase in engine torque. For air heated for isentropic conditions, the gain was 7% in torque while it was 16% for air at ambient temperature.

The experimentally found increase in fuel requirement for close to stoichiometric operation, showed that a larger quantity of mass of air was being induced. At 1,600*rpm* with air at ambient temperature, 16.8*ms* of fuel were required for no water injection, while for 5*ms* of water injected, approximately 19*ms* of fuel were required.

The maximum allowable spark advance before knock occurred was also increased with water injection. This happened for engine operation with heated where it was found that spark timing could be increased up to 42° for a fuel to water injection ratio of 4.65 as opposed to 32° for no water injection. This allowable increase in spark advance was possible for the heated operation rather than the cooler air at ambient temperature.

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