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ABSTRACT

A system for injection of diesel fuel and water with real-time control, or real-time water injection (RTWI), was developed and applied to a heavy-duty diesel engine. The RTWI system featured electronic unit pumps that delivered metered volumes of water to electronic unit injectors (EUI) modified to incorporate the water addition passages. The water and diesel mixed in the injector tip such that the initial portion of the injection contained mostly diesel fuel, while the balance of the injection was a water and diesel mixture. With this hardware, real-time cycle-by-cycle control of water mass was used to mitigate soot formation during diesel combustion. Using RTWI alone, NOx emissions were reduced by 42%. Using high-pressure-loop exhaust gas recirculation (EGR) and conventional diesel combustion with RTWI, the NOx was reduced by 82%. Perhaps the most promising results obtained with the RTWI system were the simultaneous NOx and smoke reductions during a load step transient while realizing a faster torque rise than otherwise obtainable within smoke limits.

INTRODUCTION

It has been recognized for many years that water-in-fuel emulsions are effective in reducing NOx and smoke emissions from diesel engines [1,2,3,4]. However, fixed-percentage water emulsions can result in high hydrocarbon (HC) emissions at low engine loads due to excessive reductions in flame temperature, as well as excessive increases in ignition delay across the operating range. Because of this, typical fuel-water emulsions only contain around 12% water (88% fuel), which is too low to achieve optimum NOx and PM emission reductions at high loads. Systems for in-cylinder injection of water through a separate nozzle from the fuel injector have been developed to overcome some of these limitations and are being used in production applications [5]. However, separate in-cylinder water injection is not as effective for mitigating smoke. In order to achieve simultaneous reductions in NOx and particulate matter (PM) under all engine-operating conditions, it is necessary to co-inject the diesel fuel and water, and adjust the water percentage according to the engine load. This approach is particularly appropriate for automotive engines that operate over transient cycles.

Prototype systems for direct co-injection of fuel-water mixtures have been demonstrated to achieve simultaneous reductions in NOx and PM in diesel engines with no penalty to brake specific fuel consumption (BSFC) [6,7]. In these systems, water is introduced into the fuel injector prior to co-injection of the fuel-water mixture into the cylinder. It is claimed that a fuel-water-fuel stratification may be achieved by this technique [7]. Since the water injection system is controlled on a cycle-by-cycle basis, the system is called Real-Time Water Injection (RTWI). A significant contribution to this work was conducted by Daimler Corp. [8]. The results of this work showed that water and fuel could be injected simultaneously from one injector, and that NOx and soot reduction would occur. Further research utilizing real-time water injection was conducted by Mitsubishi [9]. The Mitsubishi research differed from that of the Daimler group in that the water-fuel injection system allowed the water and fuel to mix substantially within the injector prior to the injection event. The degree of mixing of the water with the fuel did not affect the emissions reduction greatly. The Mitsubishi team reported substantial NOx and soot reductions using their water-fuel injector.

HARDWARE AND CONTROLS

The engine used for this experiment was a 1996 specification Volvo D-12, meeting 1994 U.S. on-read emissions standards. It was a heavy-duty automotive inline six-cylinder engine with overhead camshaft (OHC) displacing 11.7 liters. Although this production engine was boosted, it did not incorporate an EGR system. Therefore a fabricated high-pressure loop (HPL) EGR system was added, which included a Behr EGR cooler, a Lucas EGR Valve, and the turbocharger was upgraded to a Honeywell (Garrett) variable geometry turbocharger (VGT). A prototype diesel and water injection system, discussed in more detail below, was installed on the engine. The cylinder head was modified to accept a Kistler 6052A in-cylinder pressure transducer in one cylinder. Real-time exhaust measurements were made with a NGK fast NOx sensor and Sick Optic opacity meter. Steady state emissions measurements were made using a Milton Roy five gas emissions bench.

The water metering system was designed specifically for this testing, and it had certain objectives to meet. In summary, they were:

1. Precise metering of the water charge.

2. Instant response, particularly to down transients.

3. Electronic control integrated with the ECU.

4. Minimize corrosion-prone water-wetted parts.

5. A physically stratified distribution of fuel and water in the injected spray plume.

The design approach taken was to meter water into the gallery of the unit injector nozzle in between injection events where it would displace a similar volume of fuel and reside until it was pressurized and then co-injected. The unit injector used in this application was a “single valve” type in which injection timing and quantity control is provided by the solenoid actuated spill-valve. Since both the unit injector and the water metering system are under ECU control, it becomes possible to inject fuel-only, or a fuel/water mixture in any proportion up to the limit of the system.

The water metering system featured one metering unit per injector and therefore per cylinder. It can be understood that when water addition is requested, the injection duration for the combined fluid into the combustion chamber must increase in proportion to the quantity of water since the pumping rate remains unchanged. For any speed and load point therefore, the control logic determines the spill valve actuation duration for the fuel, and adds to it the required water duration. Should however the water metering system malfunction and not deliver the expected volume, the difference will necessarily be made up with fuel, resulting in a potentially serious over fueling on that cylinder. This would be an unacceptable failure mode, so that although not implemented for these experiments, a low cost pressure transducer in the water metering line was proposed as a “proof-of-delivery” signal if desired.

Given the requirement for accurate and reliable water metering, a positive displacement concept was chosen in which a small flange-mounted unit injection pump was driven by one of the gas exchange valve cams of the overhead camshaft. This provided a fixed immutable phase relationship to the cyclic events so that water metering took place at a time of low pressure within the EUI. Delivery volume of this metering pump was controlled using a solenoid actuated spill valve in a manner similar to that of the EUI.

To minimize the number of water-wetted precision components, this metering pump operated with diesel fuel, and its output was transferred to a shuttle metering device housed adjacent to the pump. This shuttle piston provided the separation between the hydraulic medium (fuel) and the water. The chamber on the water side was filled through one check valve from a deionized water source, and discharged through another valve to the EUI, with the displaced volume being equal to that of the metering pump output. Since the water metering assembly was mounted on the cylinder head close to the injector, the pipework volumes were low but the metering precision was high.

In the interest of minimizing the internal dead volumes within the EUI subject to high injection pressure, the flute-guided check valve in the water delivery passage going down to the nozzle was installed as close to the nozzle as possible. An opening pressure of circa 25 bar for this valve improved metering accuracy and minimized cavitation.

Several alternate strategies were considered for meeting the requirement of a stratified fuel/water spray plume. These revolved around the location within the nozzle at which the metered water merged with the fuel. It was considered that merging the water with the fuel close to the needle seat would more nearly approach the ideal in which an initial volume of fuel would be delivered, followed by either a slug of water or an emulsion. Although a design to achieve this was prepared, the work reported here was made with a simpler arrangement in which the water merged with the fuel in the below-guide gallery of the nozzle. The actual behavior of the water and fuel interactions within the nozzle before, during, and after an injection event is highly complex, and therefore the effect on stratification, if any, within the spray plume is hard to assess with confidence. The laser-based diagnostics work necessary to quantify the resulting fuel/water emulsion was beyond the scope of this study. Figure 1 shows the normalized heat release rate for a typical mid-load operation point, both with and without water, with a fixed injection timing. It was believed that if the initial injection contained fuel and water, then an observed increase in ignition delay would occur. In this case, there was no observed increase in ignition delay; however the duration of the heat release was necessarily longer due to a longer required injection event to inject the same mass of fuel into the cylinder.

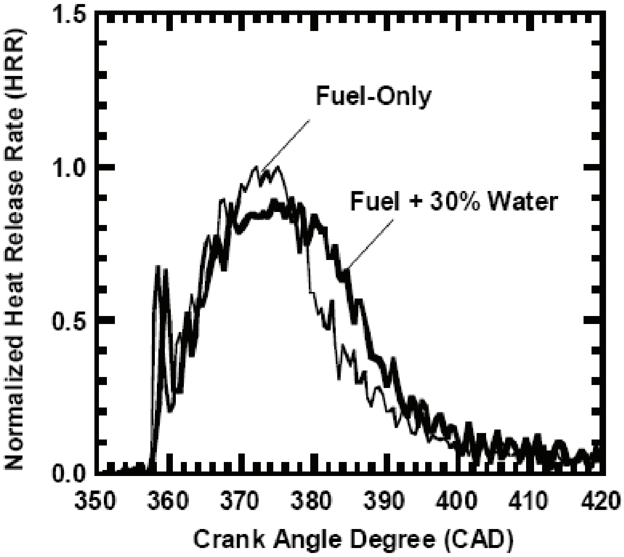

Figure 1 Normalized heat release at a typical mid-load condition

It will be appreciated that if, as is usually the case, the injection nozzle flow area has been optimized to deliver the appropriate quantity of fuel to develop the advertised torque at rated speed and load, then it will be too small for a fuel plus-water-charge for the same injection duration. We therefore have the option of leaving the nozzle flow area unchanged, in which case with a positive displacement injection system such as EUI, the injection pressure will increase in proportion to the water addition, and the risk of structural failure becomes acute. Further, the extended injection duration may increase PM emissions and the higher injection pressure may increase NOx emissions relative to baseline. Alternatively, the nozzle flow area can be increased which will limit both the increase of injection duration and pressure, but at the risk of making the injection characteristics at light load less favorable. For the work reported here, this latter strategy was chosen.

A schematic of the EUI injectors is shown in Figure 2, and a picture of the water metering system is shown in Figure 3. Figure 4 shows a schematic [10] of the complete system. Note that the unit pump is driven from a camshaft lobe, where the linear displacement of the pump transfers hydraulic action from diesel fuel to water via a shuttle valve. Individual passages from a pressurized water manifold (water pressure of 4 bar) were plumbed to the unit pumps, and then into the unit injector passages. Thus, the quantity of water introduced into the unit injectors was modulated by the closed time (pulse width) of the spill valve on the unit pump. De-ionized water was used throughout the experiment, additized with anti-corrosion (Texaco ETX6282) and lubricity additives (Lubrizol OS#129140G).

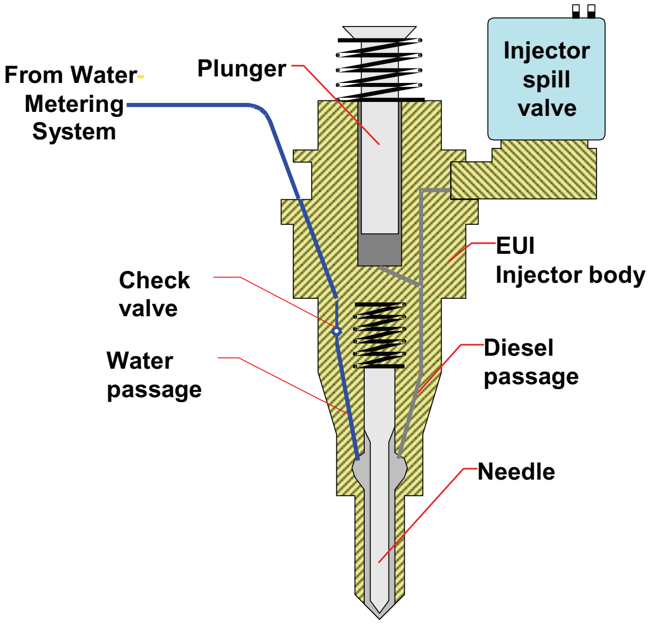

Figure 2 Schematic of Prototype Diesel plus Water Injectors

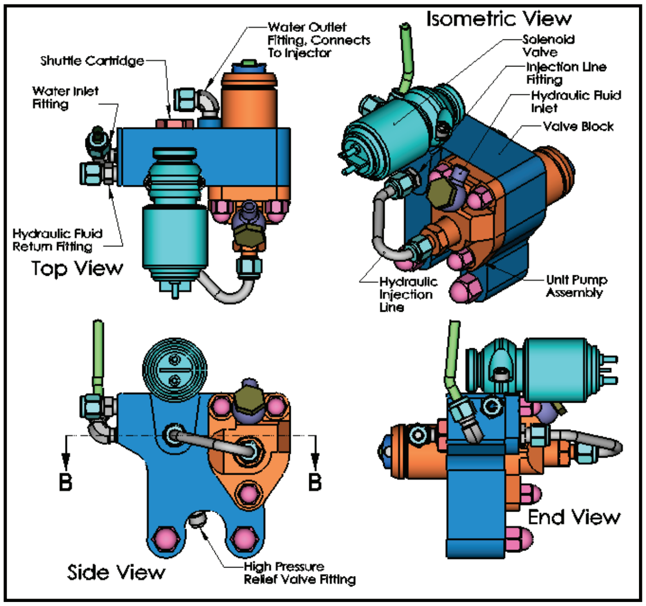

Figure 3 Mechanization of Water Metering System, Including Unit Pump, Spill Valve, and Shuttle Valve

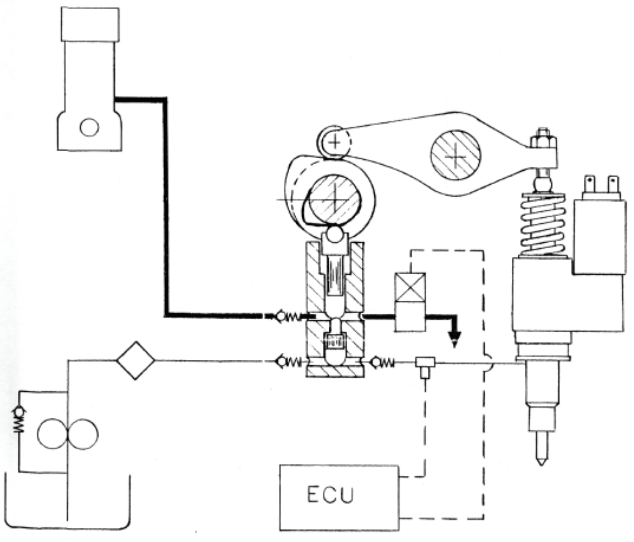

Figure 4 Schematic of Water Metering System

The RTWI injection system required synchronized control of the unit pumps for modulating water addition, and of the unit injectors for modulating the total injection quantity (fuel + water). Since both fluids were injected through the same nozzle, it was necessary to extend the injection duration of the EUI injector to accommodate the additional volume of water. The injection commands are demonstrated schematically in Figure 5. A Southwest Research Institute Rapid Prototyping Electronic Control System (RPECS) was configured to control all engine functions. The RPECS system controls the unit pumps and injectors through Delphi-supplied, bench-top, unit injector drive units. All control algorithms, calibrations, and tables, were contained within the RPECS controller.

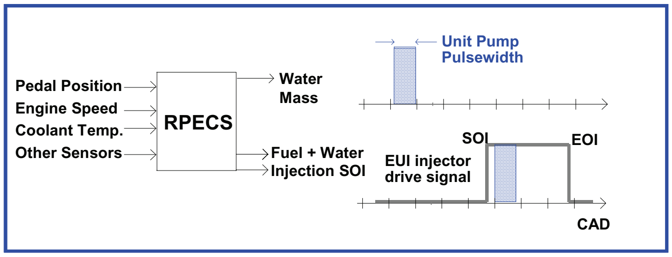

Figure 5 Schematic of Water and Fuel Electronic Commands

Despite every effort to keep the water injection hardware as similar as possible for every cylinder, constant effort was required to maintain a balanced water injection cylinder-to-cylinder. The system was regularly calibrated, yet results like those shown in Figure 6 were observed at the end of a testing day. At an equal commanded pulse width, the water flow rate varied by up to 20 mg/stroke from the lowest flowing to the highest flowing cylinder. This made measurements difficult as there was a substantial particulate reduction with water, where if a cylinder was not receiving the commanded water mass, it would produce a disproportionately high quantity of particulate emissions.

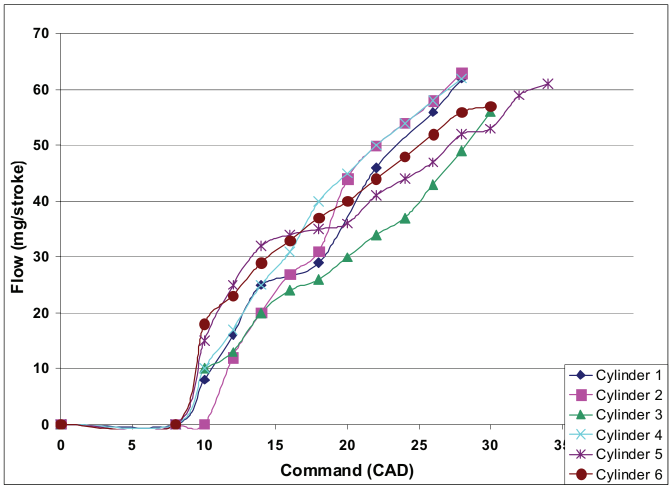

Figure 6 Cylinder-by-cylinder water mass flow rate versus commanded pulse width

STEADY STATE TESTS

Heavy-duty diesel engine emissions test cycles like the European Stationary Cycle (ESC) typically heavily weight the high load points. Additionally, on a mass flow basis, particulate matter (PM) and NOx emissions are highest at high loads. Therefore, the peak torque speed of 1200 RPM (The “A” speed of the ESC 13-mode emissions test cycle) was chosen to demonstrate the advantages of diesel/water co-injection. The torque was set to 90% of rated torque, 1845 Nm for this engine, to allow headroom in the case of an overfueling condition. Start of injection was set to 5 degrees before top dead center (dBTDC). Table 1 shows the approximate air-to-fuel ratio versus EGR rate.

Table 1 Approximate A/F ratio at the test EGR rates

EGR	Approximate A/F
0	26
5	22.5
10	30.5
13	18.7

Since the engine tests were real-time where direct feedback was necessary to set the EGR rates, opacity measurement was used as a surrogate to PM measurement. With the engine set at the appropriate speed and load, the EGR was increased until the opacity was near five percent. Then the experiment was repeated with water of varying mass co-injected with the diesel fuel, but holding opacity near one percent. The maximum water injection possible from the RTWI system as tested was 60 mg/cycle, which is equivalent to 30% of the mass of fuel injected at this load. The plotted results are labeled with the water percentage. The percentage is defined in Equation 1.

$$\%Water = \frac{Mass_{water}}{Mass_{fuel}} \qquad (1)$$

From Figure 7, clearly there was a substantial reduction in opacity by adding water. At a 1% opacity limit on diesel fuel alone, the EGR rate could not exceed 6%. However, with 30% water, the EGR was increased to more than 12%. At 1% opacity, the engine PM emissions were roughly 0.1 g/HP-hr, depending on EGR rate. At 4.5% opacity, the PM emission level was roughly 0.2 g/HP-hr. If the capacity of the RTWI system allowed for more water to be injected, it is likely that the trend would continue and higher EGR rates could be realized.

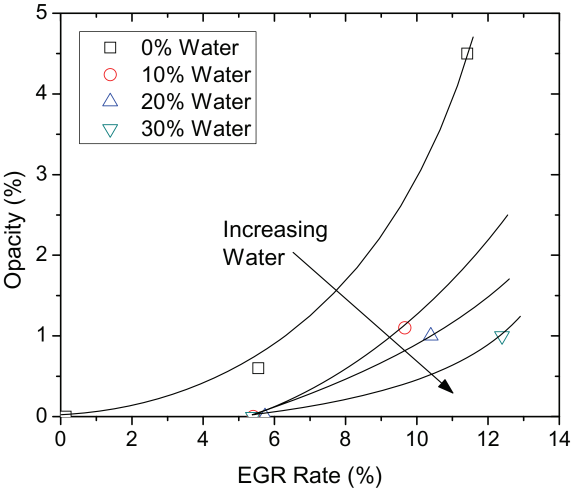

Figure 7 Opacity as a Function of EGR Rate

A PM reduction with the addition of water was expected, however a simultaneous reduction in NOx was observed as well. Figure 8 shows that diesel-water co-injection substantially reduced the NOx emissions. It appears that the NOx reduction percentage with RTWI is highest when the engine-out NOx is highest, and that the NOx reduction percentage decreases as the engine out NOx decreases. Nevertheless, even at EGR rates greater than 10%, RTWI was still effective for reducing NOx.

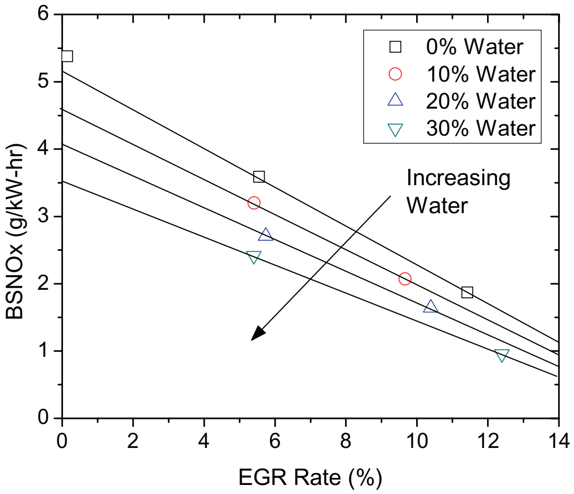

Figure 8 Brake Specific NOx as a Function of EGR Rate

NOx and PM emissions are typically the most critical exhaust species when calibrating a diesel engine because hydrocarbon (HC) and carbon-monoxide (CO) emissions are usually quite low. However, emission reduction technologies that involve a significant increase in HC or CO, like low temperature diffusion combustion or homogenous charge compression ignition, may pose problems for meeting emission targets without properly warmed oxidation catalysts. Figure 9 and Figure 10 show the effect of water co-injection on HC and CO emissions respectively. While the addition of water at low loads can hurt combustion efficiency and therefore increase the HC and CO, at high loads it does not appear to be a problem. HC emissions remained very low with a negligible effect from the water. In fact, in each grouping of data, the HC emissions were highest *without* water.

Unlike HC, CO emissions were substantially reduced with water. CO and PM emissions typically track with each other during normal lean burn diesel combustion (the previous statement is not necessarily true for low temperature diffusion combustion of HCCI). Usually it is possible to use CO limits in place of PM measurements for simple steady-state engine mapping. Therefore, it was not surprising that Figure 7 and Figure 10 resemble each other. The same mechanism responsible for the oxidation of PM is likely also responsible for the oxidation of CO.

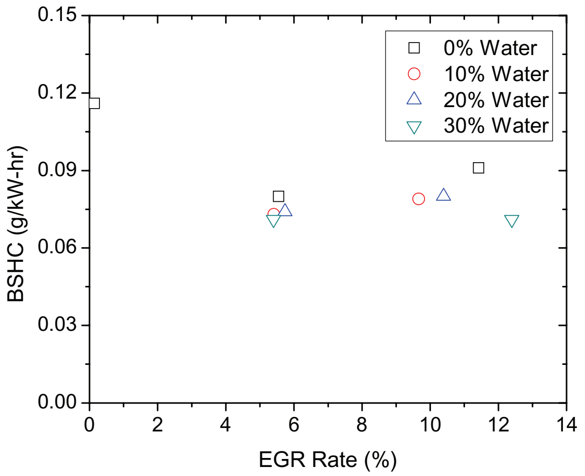

Figure 9 Brake Specific HC as a Function of EGR Rate

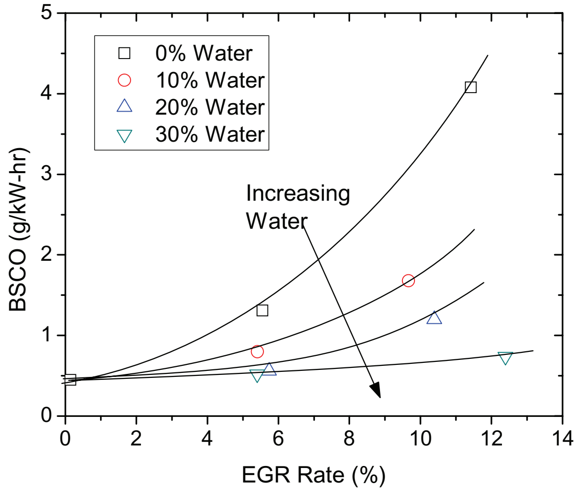

Figure 10 Brake Specific CO as a Function of EGR Rate

Unlike alternative combustion modes that can increase HC and CO, RTWI increased neither. From an emissions stand point, co-injection of water and diesel is very promising. Very large opacity and CO reductions were observed, while simultaneously, NOx emissions were reduced. There was also no negative impact on HC. However, economic pressure forces engine manufacturers to resist emission control solutions that involve an increase in fuel consumption. Most available NOx reduction strategies require the use of more fuel. Lean NOx traps (LNT) require extra fuel for rich operation to regenerate the LNT. Both LNT, and Selective Catalytic Reduction (SCR) catalysts are likely to require extra fuel for thermal management as neither system operates well at catalyst bed temperatures below 200 degrees Centigrade.

Figure 11 shows that co-injection of water and diesel also suffered from a fuel consumption penalty, although the penalty is quite small. A co-injection of 30% water increased the fuel consumption by 2%.

The fuel consumption change from injecting water is a complicated problem as there are several competing effects.

- Water in small concentrations had a tendency to increase the combustion efficiency because of more complete oxidation of PM and CO.
- There was energy consumption from injecting the water. The energy consumption was increased due to pumping the water into the injectors, as well as from the increased injection duration required to get the same amount of fuel into the combustion chamber. Both effects are accounted for in these tests.
- If the start of injection is kept constant, the addition of water retards the centroid of the injection, which leads to retarded combustion timing and reduced cycle efficiency. This effect can be eliminated by using a constant centroid location; however that was not done in this experiment.
- The energy absorption from evaporating the water will decrease cylinder temperature, and therefore the cylinder pressure acting on the piston.
- Lastly, the phase change of the water from a liquid to a gas will increase the pressure in the cylinder available for acting on the piston.

These effects compete against each other, where some increase efficiency while others decrease it. For each data point, the net fuel consumption change, whether positive or negative, will depend on the engine conditions and the injected water mass. While there may be some conditions where a BSFC penalty is observed, the fuel consumption penalty of RTWI was shown to be much less significant than the fuel consumption penalty from adding EGR for equivalent NOx levels.

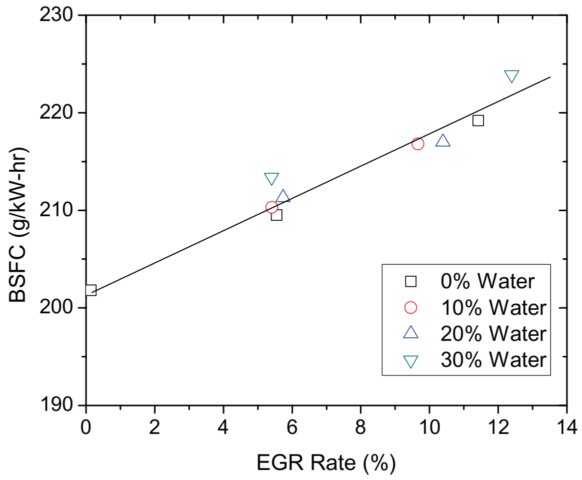

Figure 11 Brake Specific Fuel Consumption as a Function of EGR Rate

When posed with the task of reducing NOx emissions, there are several in-cylinder approaches. Most approaches have a negative impact on the BSFC. The generally preferred approach to reducing NOx is the method that meets the NOx goal with the best BSFC. Figure 12 documents several of those methods.

Before widespread use of EGR, the main method for reducing NOx was to retard injection timing. The BSFC, however, will tend to increase as injection is retarded. From Figure 12, a baseline operating condition with 0% EGR and SOI of -5 dATDC at 18.5 bar BMEP, produced 5.4 g/kW-hr BSNOx with a BSFC of 202 g/kW-hr. When the SOI was retarded to 3 dATDC, the BSNOx dropped by 40%. The fuel consumption, however, increased by 16%. Put another way, BSNOx dropped by 2.5% for every 1% increase in BSFC.

If the engine is equipped with an EGR system, then EGR is typically a more efficient means of reducing the NOx. From Figure 12, by adding 10% EGR, the BSNOx was reduced by 65% with an 8.6% BSFC penalty, or a 7.6% reduction in BSNOx for every 1% increase in BSFC.

Compared to retarded SOI or EGR, co-injecting water and diesel was more efficient for reducing NOx. By adding 30% water, the BSNOx was reduced by 42% with a 2.1% increase in BSFC, or a 20% reduction in BSNOx for every 1% increase in BSFC. The result for each of the methods is shown in Table 1.

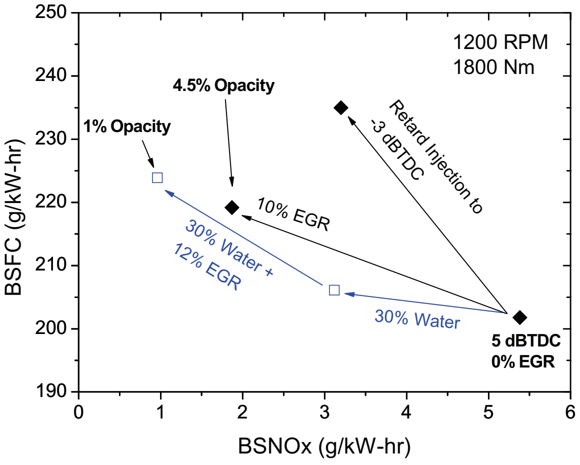

Figure 12 Comparison of Methods to Reduce BSNOx

RTWI was the most efficient approach to reduce BSNOx, however the RTWI hardware used in these experiments was limited in the total mass of water that could be injected. At this load, the maximum flow rate of water was only equal to 30% of the fuel mass. In order to further reduce BSNOx, EGR must be used in addition to RTWI. The lowest BSNOx point shown in Figure 9 represents a combination of 12% EGR and 30% water. Note that the BSNOx was reduced about 50% from a 10% EGR, no water condition.

There is an interesting synergy between RTWI and EGR. For any given engine operating condition, RTWI was demonstrated to reduce BSNOx. Similarly, EGR at any condition will reduce the BSNOx. The EGR limit for a given engine speed and load point is typically found when the equivalence ratio has increased to the point at which the PM emissions exceed some prescribed limit. If water is added while running at this limit, the PM emissions are reduced; therefore the EGR limit is increased. If the engine is adjusted to the new EGR limit, then the lowest possible BSNOx will be achieved. This synergy is demonstrated in Figure 9 as the point with 30% water and 12% EGR. When 10% EGR was added, the BSNOx was reduced to 1.87 g/kW-hr. However, the opacity was an unacceptably high 4.5%. When 30% water was added, the EGR could be increased to 12% which yielded 0.96 g/kW-hr BSNOx, yet the opacity was only 1%. The additional EGR was accompanied by the expected fuel consumption penalty from increased pumping work, but the engine out NOx is very low such that a LNT would need to be regenerated less which in turn would eliminate some of the fuel penalty typically associated with this NOx aftertreatment approach.

Table 2 Tabulated Result for BSNOx Reduction Using Various Strategies

BSNOx Reduction Technique	BSNOx	Change	BSFC	Change	BSNOx per BSFC
	g/kW-hr	%	g/kW-hr	%	%
Baseline	5.38	-	201.8	-	-
Retard SOI	3.20	-40.5	235	16.5	-2.5
EGR	1.87	-65.2	219.2	8.6	-7.6
RTWI	3.12	-42	206.1	2.1	-20

TRANSIENT TESTS

RTWI was shown to simultaneously reduce NOx and PM emissions to very low levels during steady-state operation. Perhaps it was even more important to demonstrate NOx and PM reductions during transient operation. During hard acceleration, a diesel engine is prone to producing PM emissions. There is a trade-off between the torque rise rate and the air-to-fuel ratio. Lower air-to-fuel ratios may provide faster torque rise, but will make more PM emissions. Therefore, the maximum torque rise rate will occur when the fuel is injected at the minimum air-to-fuel ratio that will not produce PM emissions in excess of the given standard. If the minimum air-to-fuel ratio can be lowered without making more PM emissions, as can be done by employing RTWI, then a faster torque rise can be achieved.

Another problem with hard acceleration is that there is typically not enough boost available at light loads to support full load fueling. The boost, which is a function of air flow, must increase before the injected fuel mass can increase. If EGR is being used, it must be turned off so that the airflow can increase. This is counterproductive for NOx emissions, and will typically increase NOx emissions on a transient test cycle as compared to a steady-state test cycle. If the NOx emissions can be reduced independently of EGR, then lower cycle-averaged BSNOx emission can be achieved.

To test the RTWI system's capability for reducing NOx and PM emissions during transient operation, as well as achieving a fast torque rise rate, a series of step load changes were performed. The step load changes were similar to the European Load Response (ELR) test cycle, but modified so that the peak load was 90% rather than 100%. The maximum load was reduced so that if there was an error in water metering where not enough water was delivered, then the engine would not be over fueled. The engine speed for the test was 1200 rpm, which represents a tough condition for building boost, and therefore a good choice to evaluate the effectiveness of RTWI. The low load portion of the test cycle lasted for 5 seconds at 10% load, followed by 15 seconds at 90% load. Figure 13 shows the graphical representation of the transient including desired fuel mass and desired water mass.

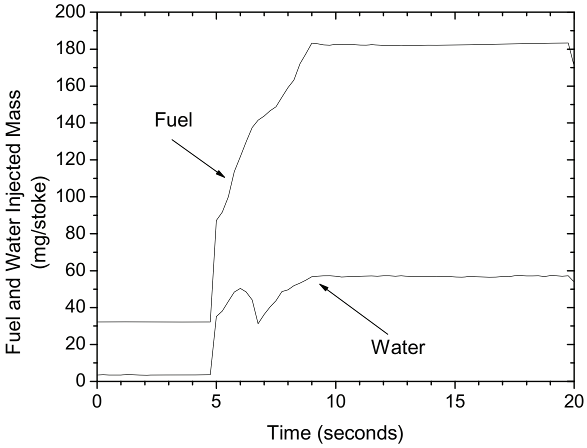

Figure 13 Injected Fuel and Water Mass During Step Transient Test

The first step load transient was with an air-to-fuel ratio (A/F) limit of 22 without RTWI. An A/F limit of 22 yielded peak opacity of around 7%, which was deemed acceptable for a step load change of this severity at this low of an engine speed. The next step load transient was with a richer A/F limit of 20, still without RTWI. The richer A/F limit showed a torque rise rate improvement at the expense of opacity as expected. Finally, the last step load transient was with an A/F limit of 20, but with the RTWI system enabled. Since the A/F limit was the same as the previous step, the torque rise was similar; however the opacity was reduced with the use of RTWI. The RTWI content was 10% at low load, the maximum quantity of water before combustion efficiency was degraded, and 30% at high load - the maximum capacity of the RTWI system.

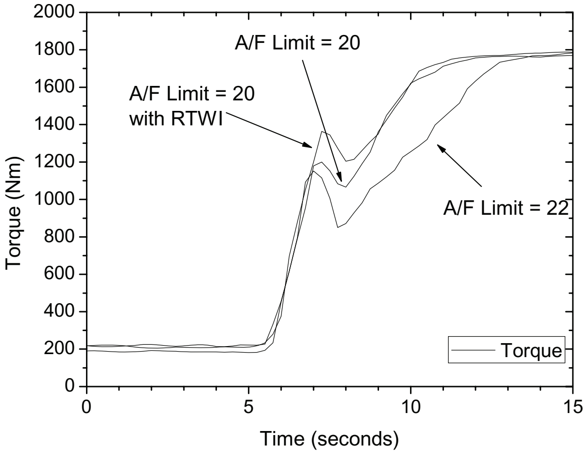

Figure 14 Measured Torque During a Step Transient Test

Figure 14 shows the torque response. Note that the torque rise was faster with a numerically lower A/F limit. This was not unexpected as the torque is primarily dependent upon delivered fuel mass. RTWI had no direct effect on the torque rise, as the torque rise with and without RTWI was very similar. Figure 15 shows the measured opacity during the step transient. Without RTWI, at an A/F limit of 22, the opacity peaked near 7% and was consistently above 2% for six seconds. Changing the A/F limit to 20 increased the peak opacity to 10%. By adding RTWI, even with the A/F limit at 20, there was no apparent opacity peak during the step transient. While RTWI had no direct effect on torque rise, the use of RTWI allowed a numerically lower A/F limit, which results in a faster torque rise. So indirectly, an engine equipped with a RTWI system can achieve a significantly faster torque rise, while the opacity is decreased as well.

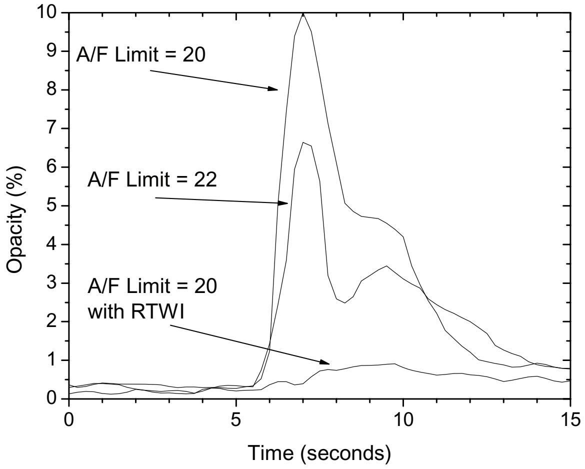

Figure 15 Measured Opacity During a Step Transient Test

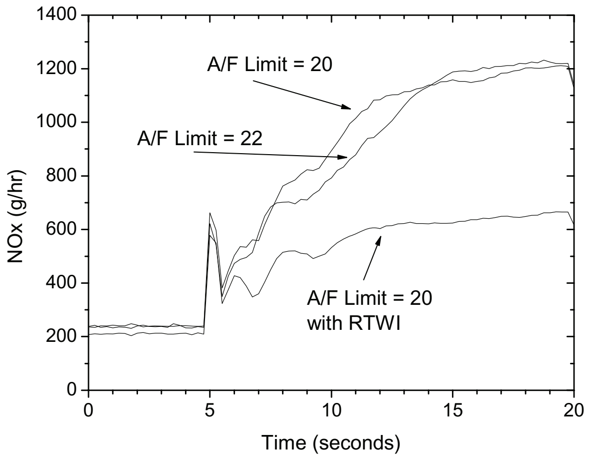

Figure 16 Measured NOx Flow Rate During a Step Transient Test

Figure 16 shows the NOx emissions during the same step transients. The low load NOx for both data sets without RTWI was very similar because the fueling at this condition is identical. The RTWI data shows a small NOx reduction, but the reduction is in line with the small amount of water that could be used during low load operation without suffering degraded combustion efficiency. The high load NOx without RTWI was somewhat similar between the data sets. A richer A/F limit tended to make slightly higher NOx emissions during the time the fuel delivery was at the A/F limit. With RTWI, the NOx was reduced by 50%. This result showed a larger advantage than the steady-state testing. It is believed that over the course of 15 seconds, the NOx had not yet equilibrated, and that eventually the NOx reduction would be more in line with the steady-state result of 40%.

CONCLUSION

In the first stage of this study, water co-injected with diesel fuel using a RTWI system was shown to substantially decrease NOx, PM, and CO emissions during steady-state operation. Further, the reductions occurred with no increase in HC, and little increase in BSFC. At high loads, best performance of the RTWI system was demonstrated when the water injection was equal to 30% of the diesel injection. The RTWI system was not sufficiently sized to deliver a higher percentage of water at high loads, so it is unclear if further reductions would be possible.

In the second stage of this study, the RTWI system was demonstrated to reduce opacity during large step load changes, which indirectly, through the use of richer A/F limits, increased the torque rise rate. The major conclusions are as follows:

1. While prepared fuel/water emulsions have been shown to reduce NOx and PM emulsions from diffusion diesel combustion, the water content of such an emulsion is fixed. The water content is usually established as the maximum amount of water that does not cause excessive HC and CO emissions at idle. The water content that meets that condition is insufficient for maximum benefit at high loads. A RTWI system where the water content can be varied from 0% at idle, to up to 30% or greater at high loads, solves the light load HC problem, and provides a much greater quantity of water at high load for a substantial reduction of PM and NOx.

2. Compared to the alternate strategies of retarding the injection timing and adding EGR, RTWI was shown to be the most efficient method at reducing NOx. Retarded injection timing cost 0.4% BSFC for every 1% NOx. EGR cost 0.13% BSFC for every 1% NOx. RTWI was significantly more efficient at only 0.05% BSFC for every 1% NOx.

3. In order to achieve very low NOx (< 1 g/kW-hr), it was necessary to use EGR and RTWI. There was a significant synergy between EGR and RTWI. EGR reduced NOx at the expense of PM. RTWI reduces both NOx and PM. On an engine without RTWI, the EGR limit occurs when EGR has been added at such quantity to increase the PM emissions to some predetermined limit. If RTWI was used, the water reduced the PM emissions so that higher EGR rates could be used before the same limit was reached. Therefore, the NOx emissions will be lower due to RTWI, but also due to the use of more EGR.

4. During transient operation, richer A/F limits could be used with RTWI. Even with rich A/F limits in place, no opacity spikes were observed. The use of RTWI nearly eliminated the measured opacity, reduced the engine-out NOx by 50%, and allowed a faster torque rise rate.

Despite the excellent results demonstrated by the RTWI system, the system was not fully optimized. Further NOx and PM reductions may be possible at high load by using a RTWI system that is unconstrained by the 30% water limit of the hardware reported here. Additionally, NOx aftertreatment technologies have significantly improved since this data was collected, which means that there is an easier alternative to reducing NOx. However, there have also been several announcements that 0.2 g/HP-hr is achievable without NOx aftertreatment. At such low NOx levels, the PM emissions are probably quite high and may require a significant amount of active diesel particulate filter (DPF) regeneration. A diesel-water co-injection system could relieve some regeneration requirement which would save fuel.

SUGGESTIONS FOR FUTURE WORK

Since the real-time diesel-water co-injection data was recorded, there have been significant improvements in NOx and PM aftertreatment for diesel engines. At the time of this work, it was assumed that engine-out PM emissions could not exceed 0.1 g/HP-hr in order to meet

US 2010 standards, hence the EGR was only added until this level was achieved. With active regeneration and a modern DPF, that number may be as high as 0.3 to 0.4 g/HP-hr. If this had been the case, the data set could have been extended to lower NOx levels. Clearly from the data shown, diesel-water co-injection was not sufficient to reach US 2010 levels; however with more EGR, there may be the possibility of meeting US 2010 standards with no NOx aftertreatment, and with PM levels sufficiently low to keep from plugging or otherwise breaking a DPF. The authors suggest that should this work be revisited, the EGR rates should be increased to very high levels to judge the true potential of diesel-water co-injection.

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