

Emission Reduction with Heated Injectors

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ABSTRACT

Fuel injectors capable of rapidly electrically heating ethanol for cold starts below ethanol's flash point temperature have been developed for the Brazilian transportation market. These injectors also enable the enleanment of 20°C cold start fueling, which has shown to reduce FTP bag emissions. Initial E-100 vehicular emission test results were published in SAE paper 2009-01-0615 [1] and presented during the 2009 SAE Congress. Further development has shown that heated injector systems can enable emission reductions with a variety of automotive fuels.

Engine control strategies which make use of heated injector systems, along with corresponding test results, are presented and discussed.

INTRODUCTION

The reduction of Hydro-Carbon (HC) emissions in internal combustion engines is a primary objective in most engine research and development projects. As emissions legislation limits set by government agencies, such as the Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis (IBAMA) in Brazil and the California Air Resource Board (CARB) in the US become more stringent, and ethanol fuels become more widely used, selecting a strategy to reduce cold start HC emissions becomes quite important.

There are many HC reducing strategies that have been identified and explored in the past. Wolfgang Samenfink et al. in SAE paper 2003-01-0627 [2] showed a comprehensive list of strategies and concepts that dealt with raw engine-out

emissions and catalyst light-off. This paper showed that reducing fuel droplet size and/or improving fuel evaporation can have significant effect on reducing HC emissions. Their work explored the use of fuel flow measures, increased system pressures, air assisted atomization and heated injectors.

The work published in this paper deals with the use of heated injectors to reduce emissions with various ethanol fuels.

Pure ethanol's (E100) flash point is 12°C. Below this temperature, there is insufficient vapor formation to create an ignitable mixture within a combustion chamber. Consequently, in order to cold start ethanol or flex-fueled vehicles down to the minimum -5°C ambient temperature experienced in Brazil, supplemental fuel systems are currently used to provide gasoline for cold starts below [typically] 18°C.

Since temperatures below 12°C are infrequently experienced in Brazil, gasoline in the auxiliary fuel tank may evaporate and/or varnish during extended dormant periods, resulting in poor quality or no-starts. It is therefore desirable to eliminate the supplemental fuel system by providing the means to vaporize a sufficient quantity of ethanol during cold starts.

The Delphi Multec® 3.5HT port fuel injector was first developed as an alternative to the supplemental fuel system. During cold engine crank and initial run conditions, a vehicle's Powertrain Control Module (PCM) commands power to an electrical heater contained within the injector. The heater raises the temperature of the delivered fuel to produce a sufficient quantity of vapor which enables an engine to start and run at low ambient temperatures.

This heated injector also enables the leaning-out of 20°C cold start fueling, which has shown to reduce both engine-out and FTP bag emissions. At 20°C, a minimum of approximately 1% gasoline (0.8% for octane and 1.2% for heptane) or 4% ethanol [3] vapor fraction in air must be present in the vicinity of a spark plug to produce a combustible mixture. Current practice to produce these required vapor percentages is to add additional liquid fuel. For example, gasoline, with a nominal 14.7:1 stoichiometric Air-Fuel Ratio (A/F), is enriched to ~8:1 during engine crank, modulating to ~12:1 for the initial run. Similarly, ethanol's nominal 9:1 stoichiometric ratio is enriched to ~2:1 A/F for crank and ~8:1 A/F during the initial run. However, enriched A/F mixtures, especially occurring before catalytic converter light-off temperatures have been achieved, increase both HC and Carbon-Monoxide (CO) tailpipe emissions.

On the other hand, when heat is applied to fuel, the required vapor can be produced with less liquid fuel, reducing start-up engine-out CO and HC emissions, which, in turn, reduces the overall quantity that the converter has to oxidize. The enleaned fueling command also increases the Oxygen (O₂) content and temperature of the engine exhaust. The combination of these factors facilitates converter light-off which reduces tailpipe HC and CO.

With alcohol-gasoline blended fuels, emission reductions decrease as the percentage of gasoline increases, because gasoline inherently produces more vapor than ethanol at 20°C. The inherently leaner calibrations with increased gasoline percentages therefore afford less opportunity to further enlean A/F commands with the addition of heat.

HEATED FUEL INJECTOR

The Delphi Multec® 3.5HT fuel injector (Figure 1) is a port fuel injector with an integrated heating device designed to heat internally-contained fuel. Electrical current supplied to two heater terminals in the injector connector is transferred to a resistive heater in the injector body. Heat generated by the resistive heater is transferred to the fuel through the injector body.



Figure 1. Multec® 3.5 HT Fuel Injector and Current Extended-tip Multec® 3.5

The initial focus of the 3.5HT injectors was to facilitate engine starting and running on ethanol at low ambient temperatures. E100 output stream temperatures, as a function of pre-injection heating times and ethanol flow rates were published in SAE paper 2009-01-0615, *Heated Injectors for Ethanol Cold Starts* [1] and presented during the 2009 SAE Congress.

Since this injector can be employed for emission reduction with fuels such as ethanol and gasoline, a heated prototype injector was operated with gasoline, ethanol and water. All three liquids were supplied to the injector at 500 kPa. No pre-injection heating was employed - the 100% heater power and 100% liquid flow commenced at the same time, remaining on for 10 seconds. A thermocouple was used to measure the output stream temperature.

As can be seen in Figure 2, of the three liquids tested, gasoline proved to have the highest increase in stream temperature above ambient, followed by ethanol, and lastly water, which had the lowest resultant temperature. Since $\Delta T = J / (C_p * Kg)$, the steady-state fuel stream temperature increase (ΔT), with equal applied heater wattage (J) and at an equal fuel mass (Kg), will level-out at a value proportional to the inverse of the specific heat (C_p) of each liquid. In other words, $\Delta T \propto 1/C_p$.

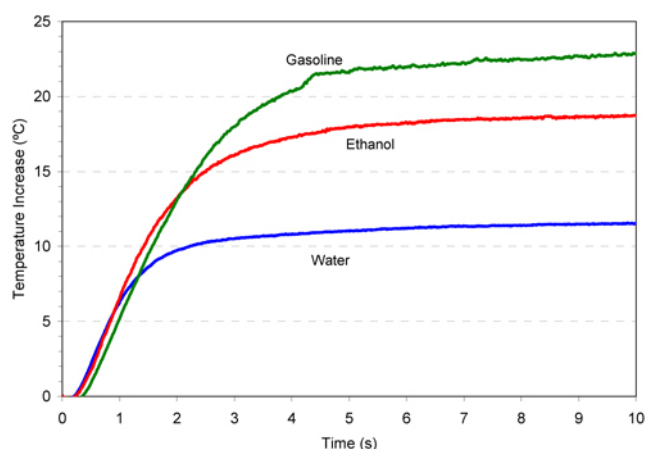


Figure 2. Increase in Stream Temperatures of Several Fluids 100% Heater Power 100% Fluid Flow

As a sense check, since the applied electrical power and fluid masses are relatively equal, the product of each fluid's temperature increase and specific heat should be relatively equal; $\Delta T \times C_p = \text{J/Kg}$ (a constant). Figure 3 shows that the products of the measured temperature increase and specific heat for each tested fluid are within $\pm 5\%$ of each other [4].

Fluid	Cp Btu/lb °F	Stream °C Increase	Cp X ΔT
Gasoline	0.53	22.9	12.1
Ethanol	0.58	19.0	11.0
Water	1	11.5	11.5

Figure 3. Comparative ($\Delta T \times C_p$) for Gasoline, Ethanol and Water

Simply stated, more heat energy is required to increase the temperature of a substance with a high specific heat capacity than one with a low specific heat. For example, since gasoline has the lowest specific heat, it readily absorbs heat, requiring the least amount of energy to raise its temperature, compared to the other liquids. Consequently, its stream temperature increase is the highest of the tested fluids.

EMISSION REDUCTION

In order to obtain a combustible air/fuel mixture at cold engine temperatures with conventional non-heated injectors, fueling is increased to generate sufficient vapor concentrations to start an engine and provide acceptable warm-up drivability. This is further exacerbated with the use of high ethanol-content fuels such as E100. Since ethanol does not vaporize as well as gasoline, the enabling of stoichiometric A/F Closed-Loop (C/L) control must be delayed, as compared to primarily gasoline fuels. Enriched mixtures lead to increased engine-out HC and CO emissions.

High engine exhaust levels of these two emissions slow reaction rates, especially at low temperatures, which delays catalyst light-off resulting in increased tailpipe emissions.

Heating fuel increases the vapor concentration for a given fuel quantity [1]. This reduces the liquid fuel mass requirement for acceptable cold starting and warming-up operation. Consequently, this permits the use of an enleaned Open-Loop (O/L) A/F calibration which is closer to or equal to a stoichiometric mixture. In addition, high-content ethanol fuels' closed-loop A/F control can be enabled earlier than without heated fuel. A leaner cold-operation mixture reduces engine-out HC and CO, and increases both the O_2 content and the temperature of the exhaust feed stream. All of these factors promote faster converter light-off times, which reduce tailpipe emissions.

With unheated fuel, port fuel injections are typically timed to impact on a closed intake valve. This avoids injecting cold liquid fuel directly into the combustion chamber, which increases the amount of unburned fuel (HC) exiting the chamber on the exhaust stroke. Conversely, when fuel heating is employed, the timing of fuel injections is calibrated to deliver the heated fuel when the intake valves are open, in order to minimize the amount of heated fuel condensing back to a liquid state (wall-wetting) within the intake port. Since the heated fuel is well-vaporized, in-cylinder wall wetting is reduced as well.

Three fuel types were tested on two stand-alone engines and a vehicle, as shown in Figure 4. E85 is used in North America and Europe. E100 and E22 are the primary fuels employed in Brazil.

Fuel	Test Platform	Engine Emission Level
E 85	1.8 liter In-line 4 SOHC stand-alone engine converter only for backpressure	Proconve 4
E 100	1.8 liter In-line 4 SOHC stand-alone engine converter only for backpressure	Proconve 4
	1.8 liter In-line 4 DOHC stand-alone engine converter only for backpressure	Proconve 4
	1.8L In-line 4 SOHC Flex-Fuel vehicle, close-coupled catalytic converter	Proconve 4
E 22	1.8L In-line 4 SOHC Flex-Fuel vehicle, close-coupled catalytic converter	Proconve 4

Figure 4. Fuels Tested on Engine and Vehicle Platforms

E85 ENGINE-OUT EMISSION REDUCTION

20°C cold start testing with E85 has been conducted with a stand-alone “test-buck” 1.8 liter In-line 4 (I4) Single Over Head Cam (SOHC) 8-valve engine. As shown in [Figure 5](#), an engine, along with its fuel supply, battery, controller, data acquisition instrumentation and user interface, is mounted on a mobile cart. This arrangement allows convenient access to all portions of the engine; the engine can also be easily transported, for example, between a garage location, an environmental test chamber or an emission test site.



Figure 5. 1.8 liter 14 SOHC test-buck engine

Since these engines are not connected to a load-absorbing mechanism, testing was conducted to simulate the first two cycles of an EPA emission test. The first two cycles are the crank and the first twenty-second, in neutral, idle modes. The engines are not equipped with active catalytic converters (inert converters are present to produce appropriate exhaust backpressure), so data acquisition and analysis focused only on engine-out emissions. Engine-out emission levels were measured and recorded with both un-energized and energized heated injectors. O/L fueling was enleaned when the heaters were energized to take advantage of the vapor created by heat; less liquid fuel is required to produce a combustible mixture. Open valve injection was employed to minimize intake and in-cylinder wall-wetting.

[Figure 6](#) shows the measured A/F (solid lines) for both the un-energized and energized heater tests, as well as the heater duty cycle (dashed line) command for the energized heater tests. The left-side ordinate axis represents the emission-lab measured A/F; the right-side shows commanded heater duty cycle. The abscissa axis shows elapsed test time. The unheated A/F ratio was produced by a 20°C cold start production flex-fuel vehicular calibration. The energized heater A/F ratio was generated by systematically leaning-out the fueling command parameters. This re-calibration also had to properly avert engine stalling, faltering or misfiring during the cold start sequence.

Heater duty cycle employed during this testing is an O/L command based on elapsed time from initiation of crank. It was derived to maximize fuel stream temperature while avoiding boiling fuel within the injector. In a productive system, the heater command would be based on a number of factors such as engine coolant temperature, ambient

temperature, elapsed time from initiation of crank, fuel flow rate and diagnostic routines.

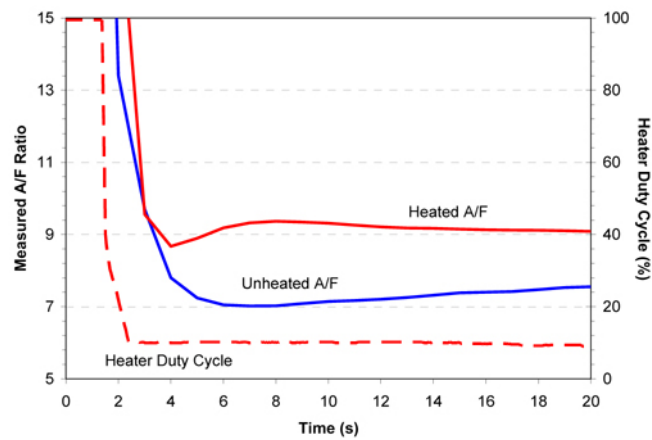


Figure 6. E85 Measured A/F and Heater Duty Cycle Command

Furthermore, in-order to avoid commanding a too-lean mixture which could result in unacceptable drivability when installed in a vehicle, the electronic throttle was manually exercised via the operator's pedal input three times in a row after the 20-second test duration had elapsed. The first excursion was a mild tip-in, the second was a part-throttle excursion and the third was a near-wide-open throttle “blip.” If the engine speed did not droop during these three throttle actuations, the commanded mixture was deemed likely to produce acceptable drivability in a vehicle. Figure 7 shows an example of these three throttle maneuvers performed during a heated fuel test. The left-side ordinate axis shows engine RPM; the right-side represents the pedal generated % load command. As can be seen, the engine RPM increases smoothly, without faltering or hesitating, for each of the three load transitions (35%, 65% and 85%).

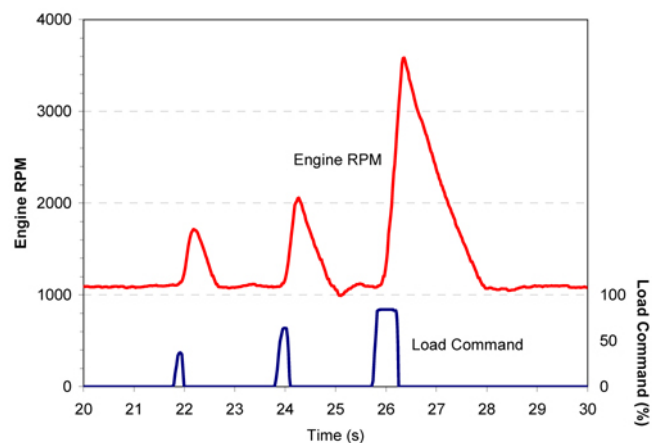


Figure 7. % Load Commands and Resultant RPM Response

1.8 LITER I4 SOHC ENGINE E85 TEST RESULTS

The enleanment in commanded A/F resulted in 67% less Total Hydro-Carbon (THC) and 70% less CO, with an increase in Nitrous Oxide (NOx) by 155%, over the duration of the 20-second test, as shown in Figure 8.

Unheated Fuel	THC [g]	CO [g]	NOx [g]
20 Second Accumulated	0.626	5.197	0.0011
Heated Fuel	THC [g]	CO [g]	NOx [g]
20 Second Accumulated	0.206	1.540	0.0028
Accumulated Reduction	↓ 67%	↓ 70%	↑ 155%

Figure 8. E85 Heated and Unheated Engine-Out 20-Second Accumulated Emissions

Although the NOx increase is a significant percentage increase in actual mass, it is actually a very small percentage of both the Brazilian Proconve Level 5 and CARB's Partial Zero-Emission Vehicle (PZEV) standards. To elaborate, if we assume that the entire engine-out mass difference of 0.0017g ends up captured in the first bag, it would be multiplied by the first bag weighting factor of [nominally] 0.057, (0.43/(3.6 + 3.9)), yielding 0.000098 weighted grams/mile. This value represents 0.081% of the Proconve Level 5, 0.12 weighted gram/mile NOx standard; 0.049% of the PZEV 0.2 weighted gram/mile NOx standard.

The data in Figures 9, 10 and 11 compares the resultant instantaneous and 20-second accumulation engine-out THC, CO and NOx mass values vs. time recorded from this engine. The left-side ordinate axis represents instantaneous mass (solid lines); the right-side shows accumulated emissions (dashed lines), the on-going summation of instantaneous mass. The abscissa axis shows elapsed test time. Both the instantaneous and accumulation curves are the average of three emission tests.