

Heated Injectors for Ethanol Cold Starts

Daniel Kabasin, Kevin Hoyer and Joseph Kazour
Delphi Corporation Advanced Powertrain - USA

Rudolf Lamers and Tobias Hurter
Delphi Corporation EMS Development - Brazil

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ABSTRACT

Ethanol is commonly employed as a transportation fuel in Brazil. However, since pure ethanol's flash point is 12°C, flex-fuel vehicles marketed in Brazil are currently equipped with a redundant fuel system which delivers gasoline during cold starts below [typically] 18°C. Since these low temperatures 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 gasoline system by vaporizing a sufficient quantity of ethanol to enable cold starts at low ambient temperatures.

A port fuel injector capable of rapidly heating ethanol above its flash point has been developed which eliminates the need for the redundant fuel system. During cold-start conditions, the vehicle's controller commands power to an electrical heater contained within each injector. The injector heaters raise the temperature of the delivered ethanol during the engine crank and initial run.

When these heated injectors are employed in conjunction with engine management system enhancements, ethanol cold start performance is similar to that of gasoline. In addition, heating ethanol fuel enables the leaning-out of 20°C cold start fueling, which has shown to reduce both engine-out and FTP bag emissions.

Heated injector flow temperature data, low ambient temperature engine cold start performance and vehicle FTP emission results are presented and discussed.

INTRODUCTION

Worldwide oil rationing in the 1970s fostered the belief within Brazil that it should become energy self-sufficient. Since at that time (and still is), the extraction of domestic oil was lower than the demand, it was thought that an alternative fuel should be developed.

Consequently, in 1974 the Brazilian government issued a strategic plan named National Development Plan - Plano Nacional de Desenvolvimento. As part of this national strategy, supported by sugar cane producers, an alternative fuel incentive plan, Pró-álcool, was issued in 1975. This plan specified that ethanol would not only be sold blended with gasoline, but also as a pure ethanol fuel. E22 (a blend of approximately 22% ethanol and 78% gasoline) and E100 (~ 94% ethanol, 6% water) were produced for the Brazilian market. Consumers could purchase vehicles either fueled exclusively by E22 or fueled exclusively by E100. The market expanded and in 1986 approximately 80% of the vehicles manufactured in Brazil were powered by ethanol fuel.

In spite of a decline in consumer demand for ethanol vehicles during the 1990s and early 2000s, due to a reduction in ethanol production and a poor distribution network, ethanol is still considered a strategic energy source for Brazil since it reduces gasoline dependence from other countries. In addition, the Brazilian government does provide incentives by subsidizing ethanol and levying lower tax rates.

The typical minimum engine cold start temperature requirement in Brazil is approximately -5°C. This requirement is of course, not as severe as the -20°C or -30°C ambient cold start requirements found in most other countries, because Brazil is a sub-tropical country.

Figure 1 is a geographical view of the minimum temperatures observed in Brazil during 2004 [1]. The city “Campus do Jordão” (altitude 2000m) is known as one of the coldest places in Brazil.

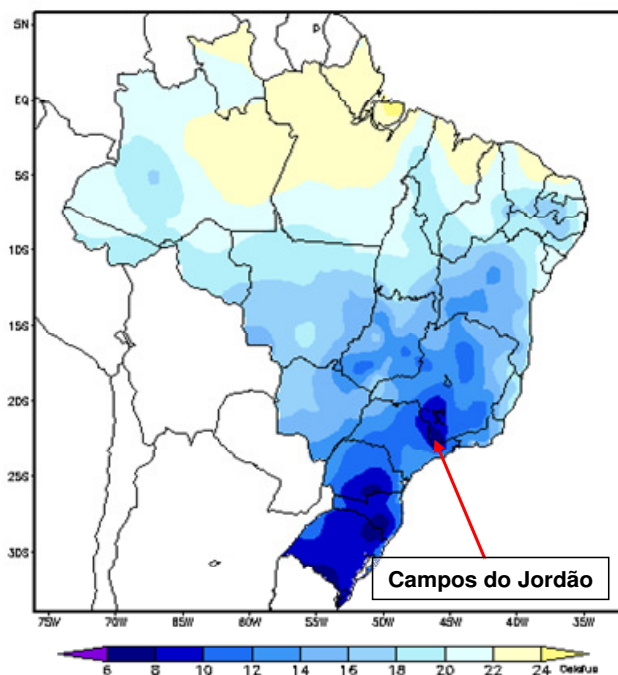


Figure 1: Minimum temperatures observed in Brazil during 2004

Figure 2 shows the maximum and minimum temperatures which were observed in Campus do Jordão – SP – Brazil during the coldest month, July of 2004, within the last 10 years [2].

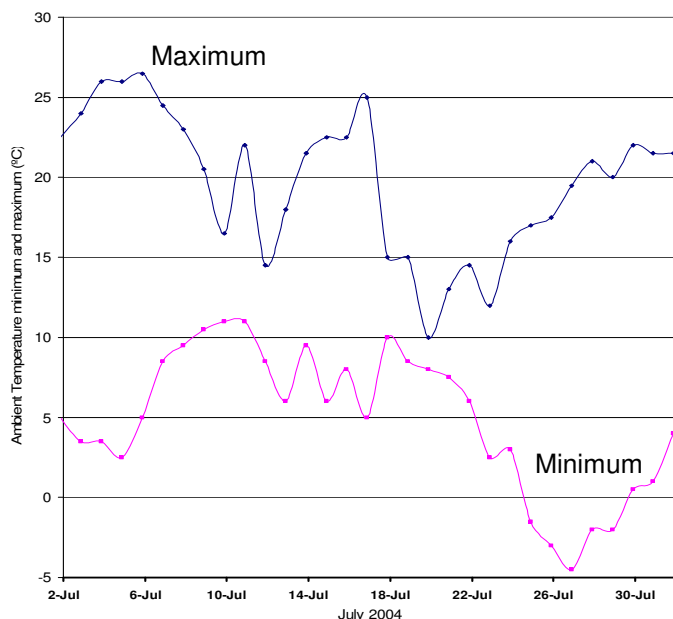


Figure 2: Maximum and minimum temperatures observed in Campus do Jordão – SP in July 2004

Brazil is now the only country that does not limit the ethanol percentage in transportation fuels; furthermore, E100 is normally marketed throughout the entire winter. Consequently, the -5°C specification guarantees startability for the entire calendar year, even when fueling with E100 during the winter months.

In order to cold start E100 fueled vehicles at ambient temperatures down to -5°C , gasoline sub-tanks systems which inject gasoline during these cold starts, were introduced in the 70's on the first carburetor E100 mono-fuel vehicles. These systems continued to be utilized, virtually unmodified, on fuel injected vehicles, as well as on flex fuel vehicles, which were first introduced in 2003.

Development of the next generation of single-fuel cold start enabling systems is underway. Heating ethanol fuel just before injection into an engine appears to be an attractive means for engine cold starting as well as emission reduction.

GASOLINE SUB-TANK SYSTEM

Brazil's auto manufacturers currently utilize an auxiliary gasoline cold-start system for cold starts which occur at ambient temperatures of [typically] 18°C and below. The system (Figure 3) consists of a small tank containing approximately 1 liter of gasoline, a small fuel pump, a solenoid valve and a calibrated orifice. The Powertrain Control Module (PCM) powers the fuel pump relay and modulates the solenoid valve to deliver a quantity of gasoline scheduled via engine coolant temperature. The calibrated orifice located either in the throttle body beneath the throttle plate or within the intake manifold, injects the metered fuel into either the plenum or the intake runners. After the engine starts, depending on coolant temperature, gasoline may continue to be injected in conjunction with ethanol delivered from the main injectors, in order to optimize warm-up drive-ability and transient throttle response. Most systems have a low-gasoline-level indicator lamp to warn the driver that refilling of the sub-tank is required.

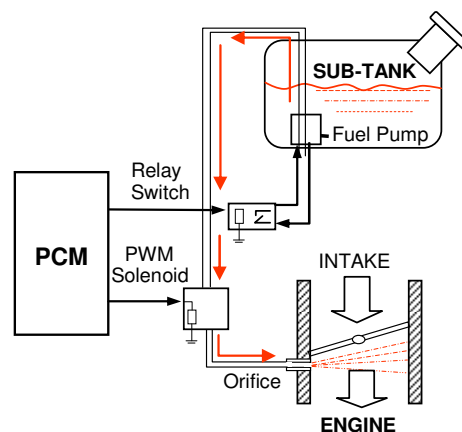


Figure 3: Gasoline sub-tank system

MODELING

In order to determine heated injector requirements, Star CD, a finite volume solver for fluid problems (CFD computational fluid dynamics), was utilized [3]. This model requires sectioning the 3D geometry of interest into smaller elements and applying boundary conditions before solving for flow parameters such as temperature, pressure and velocity everywhere within the domain. For example, Star CD can produce solutions for the temperatures of solids as well as flowing or static fluids. The fluids are injected as liquid fuel at the injector exit and are able to vaporize. Two CFD models are discussed next, a spray vapor port chamber model and an in-combustion chamber cylinder-mixing model.

SPRAY VAPOR GENERATION MODEL

A Star CD CFD computational fluid dynamics model was developed to predict what amount of vapor results from various fuel conditions within a representative quiescent cold intake port.

A picture of the CFD model of the port chamber with spray is shown in Figure 4. Ethanol liquid droplets were injected into a quiescent volume in which the air and walls were initially set to -10°C . These drops were given an initial temperature, velocity and size distribution [characterized by the Sauter Mean Diameter (SMD)] and injected at a prescribed injection profile versus time. The injected ethanol liquid drops were able to evaporate to vapor, hit the walls and stick, rebound then evaporate, or remain suspended as droplets. The amount of vapor in the port and the droplets were then measured at 1 ms after the single injection pulse was completed. Figure 4 shows an output of the spray chamber model at the end of the fuel injection pulse. The circles represent the fuel spray particles with the circle size corresponding to the liquid particle diameters (greatly exaggerated). Vapor concentration contours are plotted in color on a plane slice thru the center of the chamber.

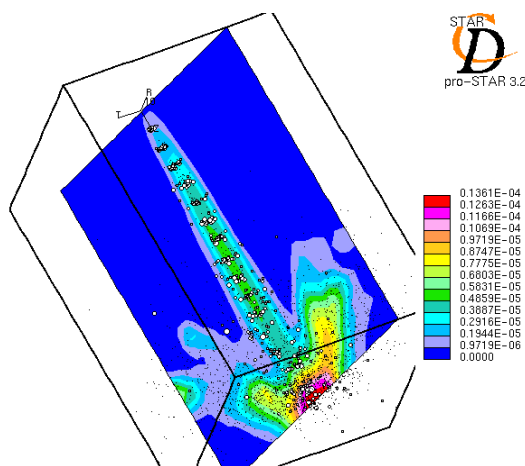


Figure 4: Spray vapor generation model representation showing liquid fuel (circles) and vapor concentration (color contours).

Test Conditions:

- One injection (0.28g pulse) of fuel
- Droplet diameter (SMD): 25, 50, 75 & 100 μm
- Droplet velocity: 25, 50, 75 & 100 m/s
- Temperature of fuel injected: $-10, 0, 10$ & 20°C

The modeling results summarized in Figure 5 indicate that increasing fuel velocity (V_{exit}) and smaller particle sizes (SMD) are beneficial for increasing vapor production, but are not nearly as effective as increasing the fuel's temperature (T_{fuel}). This figure shows that the amount of fuel vaporized roughly doubles as the SMD is varied from 25 to 100 microns. The amount of vapor created from the injection decreases as the injection velocity increases from 25 m/s to 100 m/s because the spray has less time in the air before hitting the opposite chamber wall. When the fuel temperature is raised from -10°C to 20°C , the amount of vapor produced increases about four orders of magnitude. This comparison clearly shows that the fuel temperature has the predominant effect on fuel vaporization when compared to SMD and velocity under these conditions.

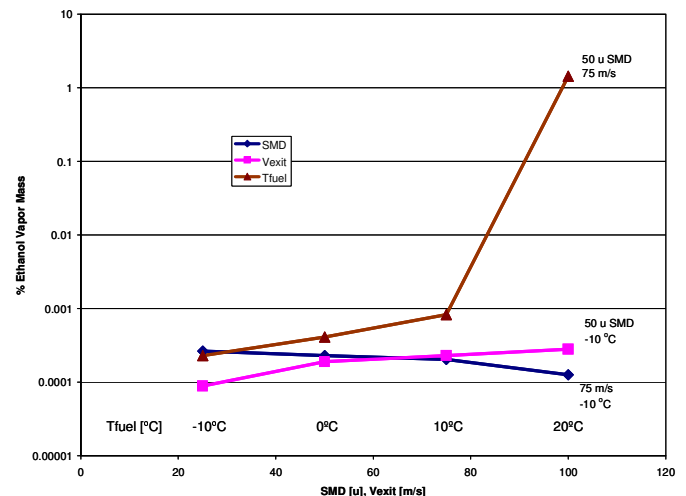


Figure 5: % Vapor mass of the total fuel mass as a function of injected fuel particle size, velocity and temperature

CYLINDER MIXING MODEL

A Star CD CFD in-cylinder dynamic mixing model, Figure 6, was developed to predict what quantity and temperature of fuel is required to initiate combustion of an ethanol-air mixture within a simplified representation of the engine cylinder, intake, exhaust ports and valves and fuel injector.

This model was used to predict the quantity of vapor present at the spark plug during -10°C cranking conditions.