Hydrogen Direct Injection Technology - Challenges and Opportunities

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ABSTRACT

This paper reviews development activities on a prototype hydrogen direct injection fuel system (focusing on the injector) intended for dynamometer research on the next generation advanced hydrogen Internal Combustion Engines (ICEs). Practical experience accumulated from specialized material testing, bench testing and engine operation have helped direct research efforts on the fuel injection system.

The highly developed and reliable internal combustion engine technology continues to get more sophisticated. Adapting such ICEs to utilize hydrogen can result in cost effective power plants that can serve the needs of a long term hydrogen roadmap. Hydrogen direct injection provides many benefits including improved volumetric efficiency, combustion robustness (avoidance of pre-ignition and backfire) and yields significant power density advantages relative to port-injected approaches in hydrogen ICEs. Early, mid or late-cycle direct injection timing approaches allow engine developers maximum flexibility to optimize higher power density, efficiency and low emissions.

A comprehensive development methodology was adopted to address various technical challenges encountered during the development process. Specific hydrogen-related issues with injector sub-components are described. As will be seen, hydrogen has presented unique materials related challenges and opportunities. Technical discussion looks at the effect of hydrogen's low mass / energy density, high sonic velocity and low viscosity. These physical attributes directly affect component size, material choice, wear rates and diffusion effects. Chemical effects due to hydrogen must also be considered as they directly affect component life. Current efforts and plans to address these technical hurdles through are also briefly discussed. Successful resolution of these issues will bring the technology significantly closer towards the ultimate goal of commercialization.

1. Background

For the transportation sector, hydrogen internal combustion engines utilizing direct injection are viewed as a high efficiency / low emission technology for bridging the transition process to the hydrogen economy based upon fuel cell technology. It has been estimated that a hydrogen direct injection (DI) engine can be integrated into a hybrid vehicle system which would demonstrate fuel consumption (fuel energy per unit distance) that is within 15% of a vehicle of similar size with a hybridized fuel cell system. The lower hardware cost (as compared to present fuel cell systems) and use of existing manufacturing facilities for conventional reciprocating engines makes this an attractive consideration. Some engine manufacturers have identified robust fuel injection technology as one of the key enablers for

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commercialization of advanced hydrogen DI engines. This paper deals with engine level issues and focuses on the injector technology.

Other key enablers for a hydrogen transportation system are fuel storage and reliable supply of low cost hydrogen fuel. The production of hydrogen fuel ideally, should use production methods that minimize greenhouse gas emissions. These issues (production/supply and storage) are not dealt with in this discussion. But it is recognized that they are also essential for the ultimate success of any significant penetration of hydrogen in the transportation sector.

The basic hydrogen injector architecture reviewed here, had been originally designed and developed for natural gas engine programs. The objective of this work was primarily to understand fundamental issues limiting injector durability and identify potential methods to improve life. The current injector, in this study, is only considered to be a research tool for developing engine /fuel system technology and demonstrating engine trends. It is not our intention to represent this injector as a prototype for production, but rather uncover fundamental issues relevant to future production intent injector architecture.

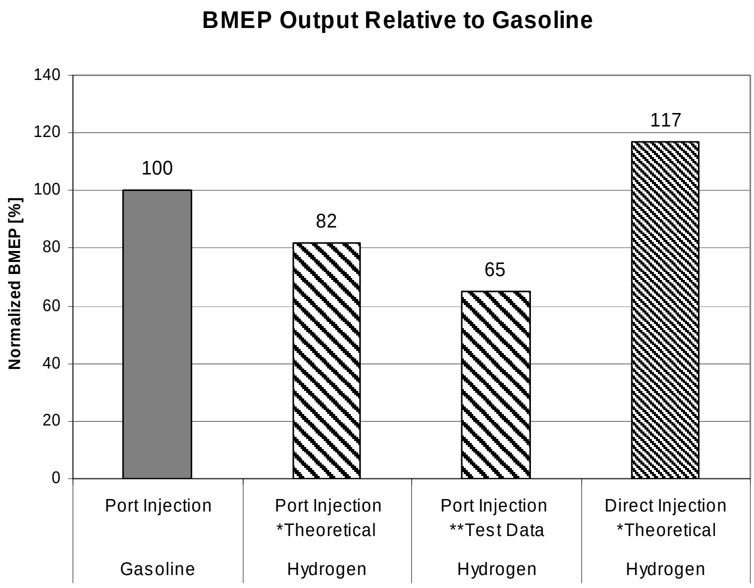
Compared to liquid hydrocarbon fuels, hydrogen is a challenging fluid to use in precision injectors because it has very low viscosity, low density and presents certain chemical challenges. The goal of this work was to understand basic mechanisms that limit injector life and identify promising technology strategies to provide significant improvements that are planned in the next phase. Operational experience on an experimental hydrogen DI research engine has provided many hundreds of hours of “real world” test experience to help expose weaknesses in design or material selection. Research on a single cylinder hydrogen DI engine has confirmed significant potential for very low emissions, high efficiency and high performance. The engine testing is significant for the injection system because it is very difficult to replicate or model the entire set of thermal, chemical, and mechanical effects – usually only a few aspects are reproducible on a test rig for example. Nonetheless, specialized research rigs and tools did provide insight into different degradation mechanisms. Fundamental data and early understanding has started to emerge as a result of extensive single-cylinder engine testing and recent test bench work with a hydrogen autoclave (with 1 to 300 bar, and 20 °C to 300 °C capability). Limited environmental effects of an injector sub-components installed in the cylinder head of an engine have been reproduced.

This report references collaborative research activities at Ford’s Research Innovation Center (Dearborn, MI, USA), and Pacific Northwest National Labs (Richland, WA, USA), and Westport Innovations Inc. (Vancouver, BC, Canada).

2. Direct Injection Engine Technology – Opportunities & Results

General Engine/ Fuel System Description

For much of the work, the hydrogen direct injection engine generally uses a centrally mounted injector, with a 4-valve layout much like a modern diesel engine. Direct injection can eliminate engine tendency to backfire in the intake manifold and minimizes pre-ignition tendency. This is because there is no combustible mixture in the intake manifold. And ignition occurs well after the intake valve closes.



Data sources: Reference 1 and 2

Figure 1: BMEP Output Relative to Gasoline

Injector Environmental Parameters			
	Minimum	Nominal	Maximum
Body Surface Temperature	-40 ºC	90 ºC	125 ºC
Nozzle Tip temperature	-40 ºC	200 ºC (est.)	300 ºC (est.)
Fuel Pressure	50 bar	100 bar	250 bar

Table 1 - Injector Environmental Conditions

Direct injection can greatly increase the opportunity to maximize power density [1, 2] over a port-injected engine (Figure 1). In port injected engines, at stoichiometry, an 18% in loss of power (relative to gasoline) occurs because of air displacement by hydrogen. In practice this level of fueling is difficult to achieve without backfiring (unwanted pre-ignition) when the intake valve is open, especially at higher loads. As a result there is a further de-rating of a hydrogen port engine, such that it is only able to demonstrate 65% of the torque (or BMEP) that a similar sized gasoline engine can achieve. Conversely, direct injection hydrogen engines, can exceed the output of a gasoline engine. A properly designed turbocharging system can dramatically raise the potential output of the hydrogen engine further, just as it does for a diesel engine or direct injection gasoline engine.

In current research, hydrogen is typically injected at pressures between 50 bar and 250 bar depending on the engine combustion strategy. Late injection (near TDC), especially on engines with turbocharging will require higher hydrogen injection pressures to overcome higher peak cylinder pressure and have maintain sonic fuel flow at the nozzle. Earlier injection results in a more homogeneous fuel/air mixture. After the fuel mixture is prepared, it is then later ignited with a spark plug. Fuel can also be injected after ignition occurs if the fuel pressure is significantly higher than the cylinder pressure. In this environment, the external surface of the upper injector body which is in contact with the engine oil (under the valve cover) and cooling jackets of the cylinder head, runs at temperatures on the order of the engine coolant (i.e. 90 ºC) when the engine is fully warmed up. Table 1 summarizes the environmental conditions to which the injector is exposed. The tip of the nozzle is exposed to the highest temperatures from direct contact with the combustion chamber.

Injector Design and Function

In an effort to provide high instantaneous flow with hydrogen (about 4 g/sec to 6 g/sec instantaneous flow, with 100 bar supply), a new injector family was developed from a similar natural gas research injector. This injector (J43Px series) uses piezoelectric actuation in place of magnetostrictive actuation previously used for natural gas injectors. Greater detail and the development history of this injector have been previously reviewed [3].

In simple terms, the injector is composed of 4 main sub-assemblies (figure 2):

1. **Body & cap –** which contains the pressurized fuel
2. **Piezoelectric actuator –** to provide opening / closing motion of the moving parts
3. **Hydraulic compensator –** allow passive adjustments for variation in parts tolerances during assembly, thermal changes during normal operation and normal wear over the life of the injector.
4. **Needle and nozzle–** which directs and controls the flow of fuel into the combustion chamber.

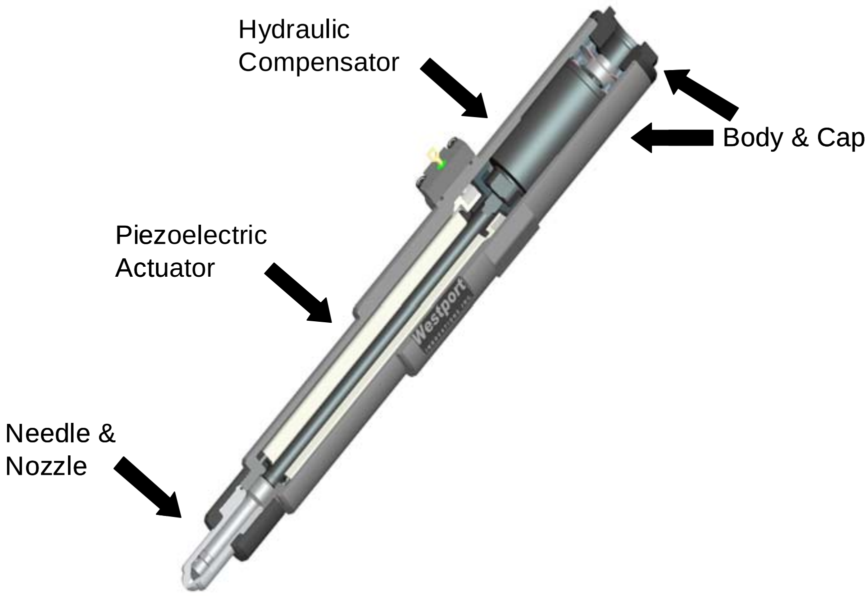


Figure 2 - J43Px Injector Sectioned

To open the injector, electrical charge is applied to the piezoelectric actuator in a controlled manner with a special electronic driver. As the piezoelectric element lengthens (up to about 100 micron or 130 micron, depending on actuator model), it pushes on the hydraulic compensator which in turn lifts the needle. Over the very short injection period, typically 5 msec or less, the relative motion inside the hydraulic compensator is minimal. As the needle lifts, it admits hydrogen through the nozzle, roughly in proportion to the needle lift. At the end of the injection period, the electric charge is drained from the piezoelectric actuator, its length is reduced and the whole assembly returns to the closed position.

It can be seen from the above description that injector is normally closed when de-energized. It is also noteworthy that special circuitry in the injector (bleed resistors) and the electronic driver are used to guarantee closure of the injector for any failure mode involving the main harness or driver circuitry. The electronic driver was developed, like the injector, for engine research in a test cell. A future injector driver design, which is more compact, would need to be developed for multi-cylinder engines or vehicle demonstration.

Early research examined possible interactions between the piezoelectric ceramic material and the hydrogen fuel, but there were no significant issues during short term exposure. As will be discussed later, after further research some minor issues have been identified with the epoxy coating on the actuator itself.

450 V and 1000 V versions of this injector (J43P2 and J43P3, respectively) have been used in engine testing. The J43P2, uses a shorter, lower stroke actuator and hence has peak flow of only about 4 g/sec at 100 bar supply pressure. Modeling and tests indicate that the 450 V actuator develops about 1100 ppm linear strain in this application due to limitations on the stack design. The lengthened J43P3 version was built, with a better optimized piezoelectric stack and a new driver. This new actuator develops about 1450 ppm linear strain at a peak voltage of 1000 V; it has shown significantly increased flow of about 5.5 g/sec at 100 bar supply pressure (figures 3 & 4). The higher voltage stack uses thicker elements and therefore has fewer joints and more functional piezoelectric material. The main disadvantage of the 1000 V design is that specialized electronic high voltage components are required.

Both injectors can function well at up to about 250 bar as the working pressure. Flow increases linearly with pressure. However, depending on the exact conditions, diminishing or negative returns will occur above 200 bar. This is related to differential pressure effects on the needle. In practice, researchers are often limited by the configuration of their laboratory fuel supply systems and safety rules.

The needle which is directly actuated (no levers or amplification method) by the piezoelectric element is capable of multiple injections and variable lift. Special electronic drivers were developed for 2 different actuator sizes (450 V / 90 micron and 1000 V / 130 micron), which allowed control of the needle position.

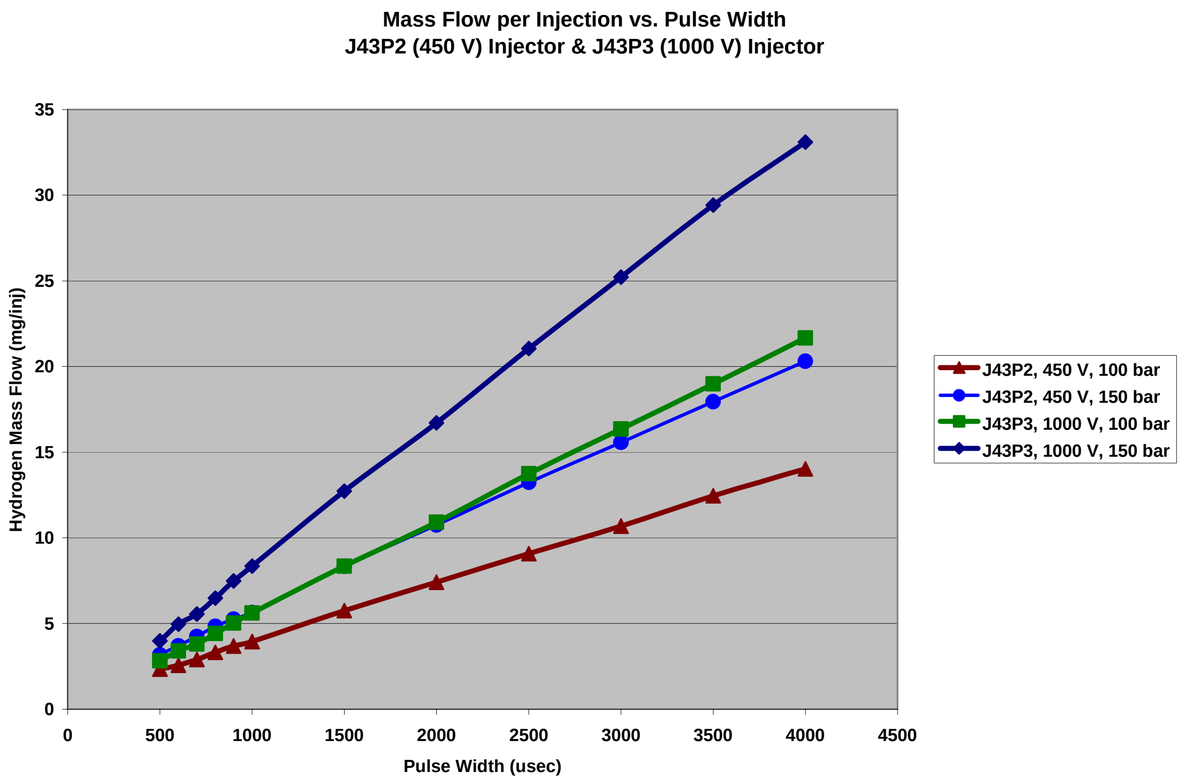


Figure 3 – Mass Injected vs. Pulsewidth for J43P2 and J43P3 Injector

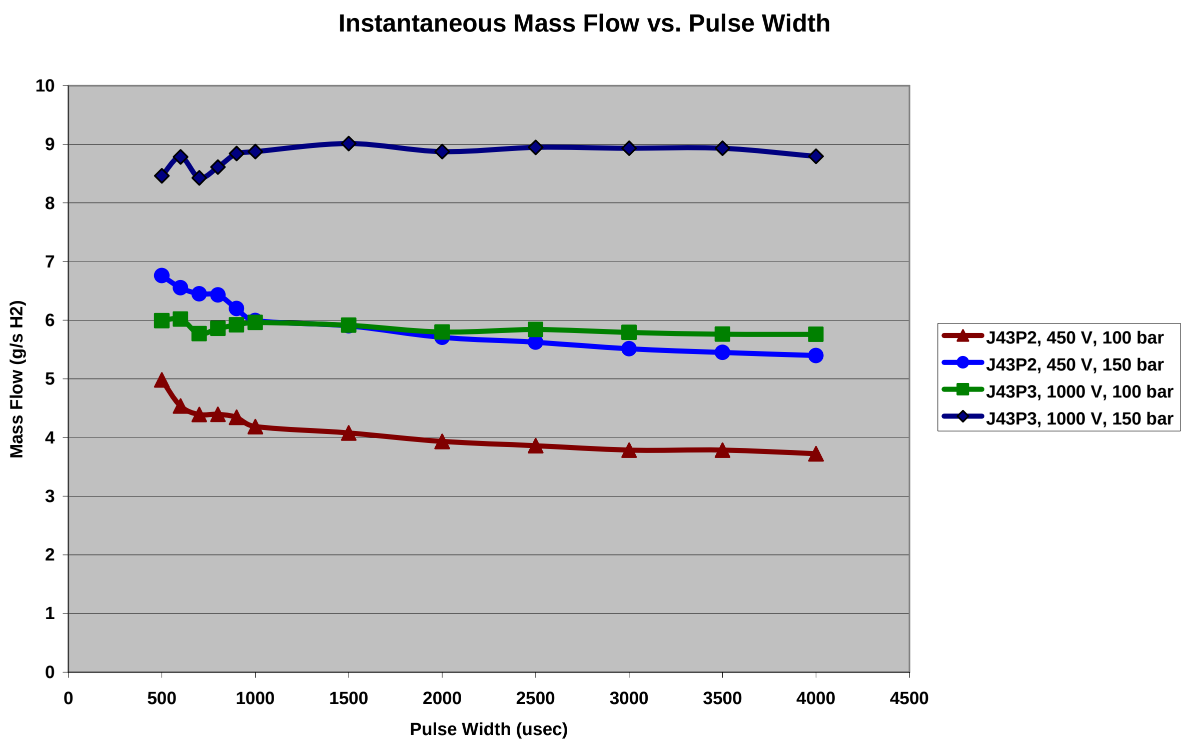


Figure 4 – Instantaneous Mass Flow for J43P2 and J43P3 Injector

In terms of needle lift control, it can be seen (figure 5) that different peak voltage applied to the piezoelectric actuator causes the cycle average flow rate (and instantaneous peak flow rate by inference) to vary roughly in proportion to voltage. These particular test results were on a test bench with air at 150 bar, used a fixed pulse width (1.5 msec) and fixed injection frequency (1000 injections per minute – equivalent to 2000 engine rpm). The data reflects the lack of flow at voltages below 400 V; during this range the actuator is relieving the elastic deformation inherent in the needle, seat and other components. Once open, a steady increase in gas flow is evident up to an average mass flow of approximately 0.7 g /sec of air at 1000 V. This is equivalent to 28.5 g/sec instantaneous flow of air, which equates to an instantaneous flow of about 7.1 g/sec for hydrogen. The flow becomes limited at higher voltages as the choking point moves from the needle/seat to the nozzle holes.

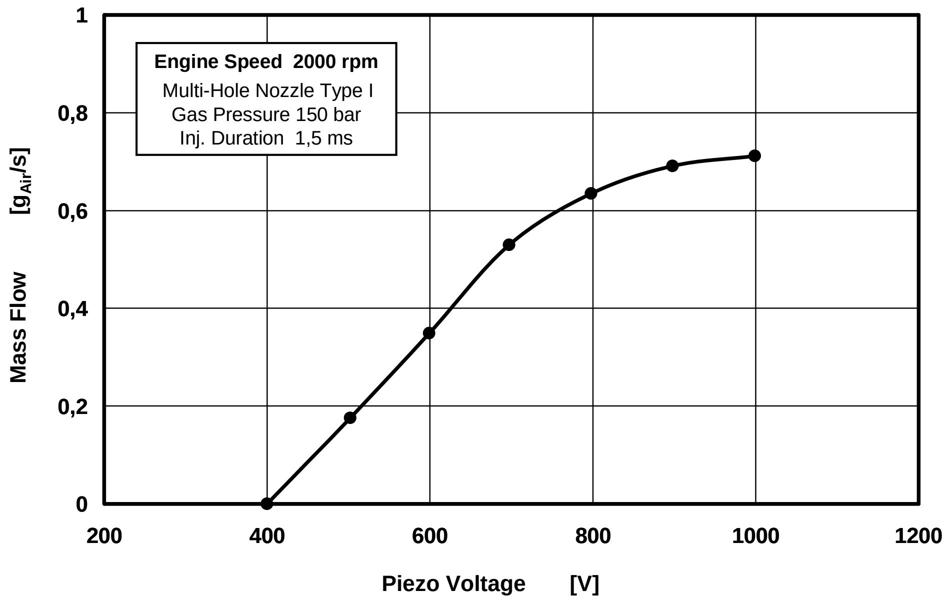
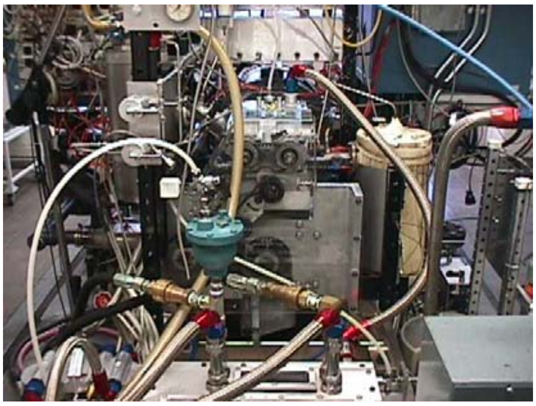


Figure 5: Mass Flow (Air) vs. Peak Voltage for a J43 Piezoelectric Injector

Hydrogen Single Cylinder Test Cell Results

Recent engine development work described here has been performed at Ford Motor Company using a single cylinder research engine to determine the benefits and challenges of direct injection with hydrogen. The approach was to investigate the effects of injection with regards to engine efficiency, emissions and power density. Injector performance was closely monitored including flowrate, response and dynamic range over many different rail pressure and engine conditions. Durability related measures such as static leakage versus pressure and operational time were also closely tracked. A picture of the test cell and some specifications are shown in Figure 6.

Hydrogen's wide flammability limit allows great freedom of injection strategies within which to operate the engine. In spark ignition mode, gasoline type fuels generally create high levels of CO and soot if injected as a liquid into the combustion chamber after spark, but with a carbon free fuel this of course is not limitation.



Type	Ford single cylinder design
Bore	80-92 mm, 89 typical
Stroke	80-100 mm
Displacement	0.4 to 0.6L
Compression Ratio	Variable (approx.) 9:1 to 16:1
Rated speed	6000 RPM
Max. speed	7000 RPM
Max. cylinder pressure	120 bar
Number of valves	2 intake, 2 exhaust
Valve Sizes	35mm intake 30mm exhaust
Valvetrain	DOHC, direct acting mechanical bucket, toothed belt, 230 deg duration event
Max. valve lift	9.5 mm / 9.5 mm
Lubrication	Dry sump
Cylinder liner	Wet

Figure 6: Test Cell and Engine Specifications

As shown in Figure 7, four basic injection strategies as related to engine bottom dead center (BDC), intake valve closure (IVC) and combustion (TDC) positions are shown in both a low load and high load condition. With a sufficiently fast response injector, it is possible to further divide each injection event into multiple injections for additional mixing control to further optimize efficiency and NO_x emissions.

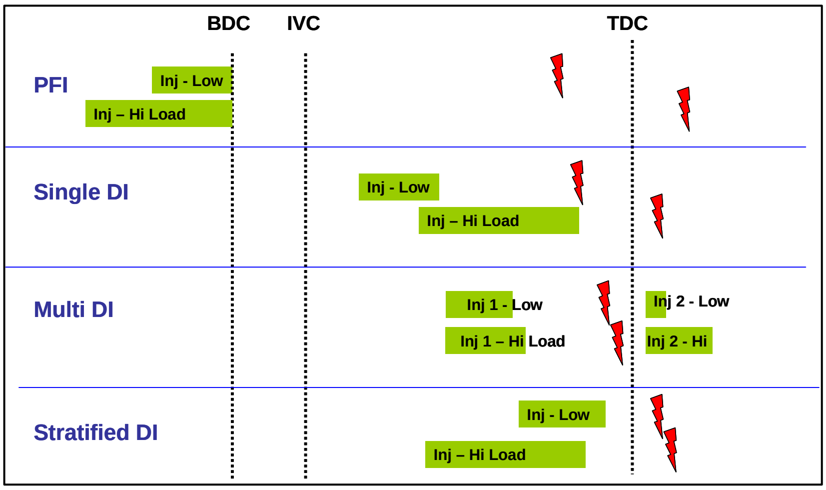


Figure 7: Comparison of Various Injection Strategies

Results for indicated specific fuel consumption (ISFC) and NOx for these four basic injection modes is shown in Figure 8. With port fuel injection (PFI), a homogeneous mixture in the intake port can be subject to backfire, especially if it is present during overlap conditions and at high equivalence ratios. Timing the port injection to occur only during a portion of the intake stroke has been shown to mitigate backfire occurrence, but still displaces air (30% at stoichiometry), thus penalizing the volumetric efficiency and power density potential.

Direct injection can offers both improved efficiency and reduced NOx versus PFI across all equivalence ratios that were evaluated. In particular, multiple injection at phi > 0.6 can offer nearly an order of magnitude of NOx reduction with only a slight penalty in efficiency versus single injection. One consideration for this particular combustion mode is to have sufficient rail pressure for flow control, since it occurs near peak cylinder pressure conditions.

Stratification of the air/hydrogen mixture can also be used to minimize heat losses. Table e 2 summarizes some of the inherent versus injection process related benefits of direct injection as compared to port fuel injection.

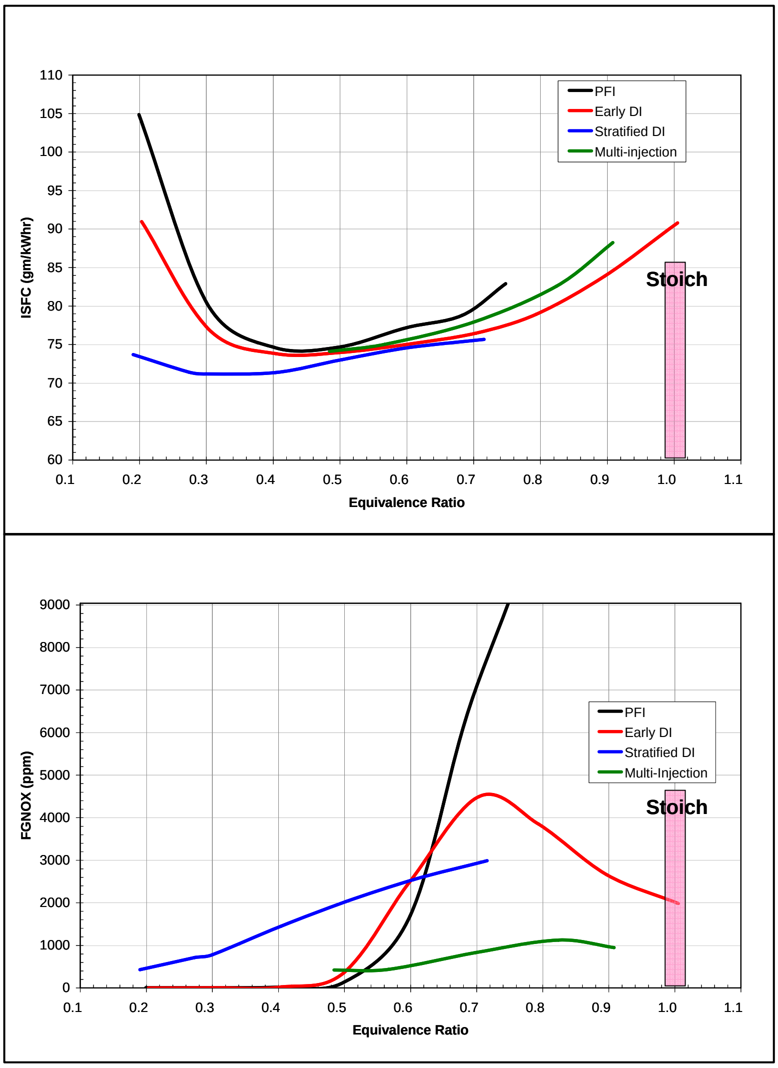


Figure 8: Indicated Fuel Consumption and NOx vs. Equivalence Ratio, 1500 RPM

Inherent	Injection Process
Power density improvement Air is not displaced by H2 during intake stroke	**Reduced thermal losses with charge stratification** minimal wall contact with fuel
Elimination of backfire H2 injection after intake valve closing	**Low NO_x, multi-injection strategies**
Recovery of a portion of tank energy Ideally inject at TDC Tank 350 or 700 bar, rail 20-250 bar typically	**Pressure rise rate control with multi-injection**
Reduced pre-ignition tendency Late injection results in less compression heating, in-cylinder residence time and exposure to hot spots	**Improved thermal efficiency** Increased compression ratio potential

Table 2: Some Advantages of Direct Injection vs. Port Fuel Injection

By injecting very late in the compression stroke, stratification allowed by direct injection can greatly increase the burn-rate, while minimizing wall contact and the associated heat losses. The nozzle design is key to optimizing this stratification. Figure 9 shows a comparison early (Single DI) vs. Late (Stratified DI) injection at an equivalence ratio of 0.4 under equal efficiency conditions.

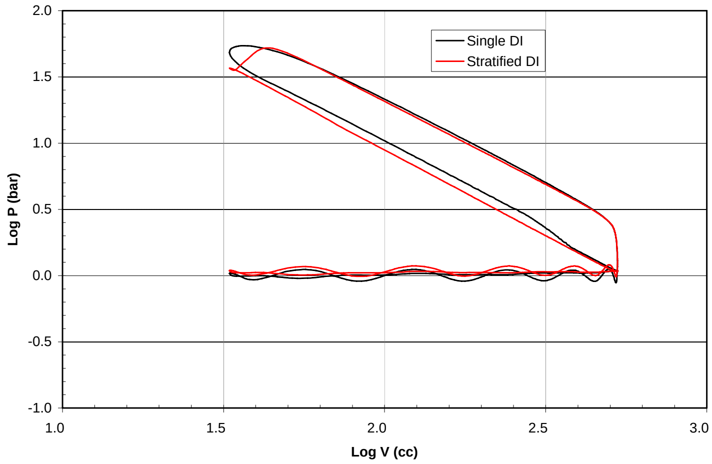


Figure 9: Cylinder Pressure for a Stratified versus well mixed injection case, Phi 0.4

The very rapid combustion speed of a stoichiometric hydrogen/air mixture can be a NVH (noise, vibration & harshness) concern, especially at full load. As shown in Figure 10, pressure rise rates of over 10 bar/deg have been observed. A multiple injection strategy offers a potential solution to this issue, provided the injection system is capable.

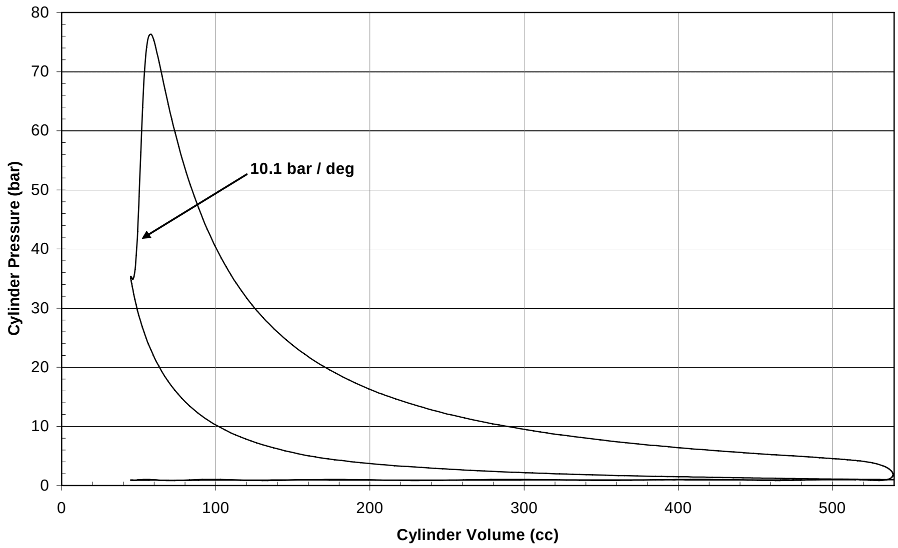


Figure 10: Pressure Rise Rate, Phi = 1.0, 2000 RPM

A key focus of Ford's approach to hydrogen engine development is to pursue efficiency improvements. Cycle fuel efficiency directly addresses customer fuel costs, on board storage requirements and range. With the goal to exceed automotive Diesel efficiency levels, the test program continually developed the single cylinder research engine. When applying published friction levels from a production multi-cylinder engine (0.7 bar @ 3000 RPM per FEV, 4.8L), a brake thermal efficiency of 45% is obtained, as shown in Figure 11. One of the 2010 FreedomCAR goals for H2ICE's is a peak thermal efficiency of 45% [5].

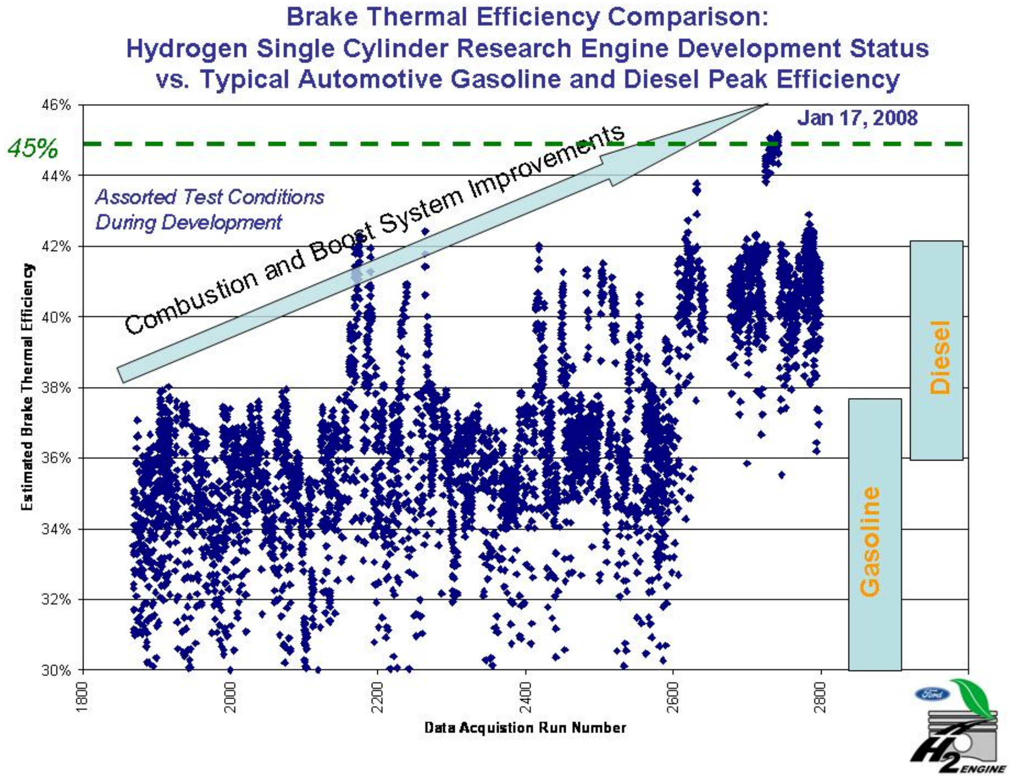


Figure 12: Brake Thermal Efficiency Status

3. Fuel System Technical Challenges with Hydrogen

The hydrogen environment presents a number of fundamental challenges as compared to the injectors which are designed for liquid hydrocarbon fuels (gasoline or diesel) or even natural gas. The basic properties of gaseous hydrogen contribute directly to challenges, in particular issues with long term durability and to a lesser degree with basic performance. This section breaks down the key issues from the point of view of basic fluid properties. Finally the effect on individual injector sub-components is examined.

Comparative Fuel Properties (at 80ºC and 25 MPa)

Property	units	Diesel (1-D)	Methane	Hydrogen
Lower Heating Value	[MJ/kg]	43	50	120
Speed of Sound	[m/s]	1240	579	1625
Density	[kg/m^3]	727	144	15.1
Dynamic Viscosity	[cP]	0.836	0.020	0.011
Energy Flowrate* (LHV) - 1 mm^2 hole	[MJ/s]	8.19	1.66	1.34
Flow Regime	[-]	Sub-sonic	Sonic	Sonic

*back pressure = 0.1 Mpa

Table 3 – Fuel Properties Comparison

Design Constraints with Hydrogen

Flow rate

Per unit area, liquid fuels can deliver more potential fuel energy (lower heating value), at the same differential pressure. This seems intuitively obvious due to their higher density (figure 12). But other factors need to be considered such as whether the fluid is incompressible or compressible and whether conditions dictate whether flow is sub-sonic or sonic. As can be seen in table 3, a 1 mm^2 orifice with diesel will deliver about 6 times as much chemical energy (LHV), at the same differential pressure, as would a hydrogen injector. Also note that the liquid diesel flow is still subsonic at this condition (25 MPa supply) whereas both gases (hydrogen and methane) quickly accelerate to sonic conditions and choke (Mach number = 1) in the narrowest section of the injector, usually under the needle/seat interface or the nozzle holes.

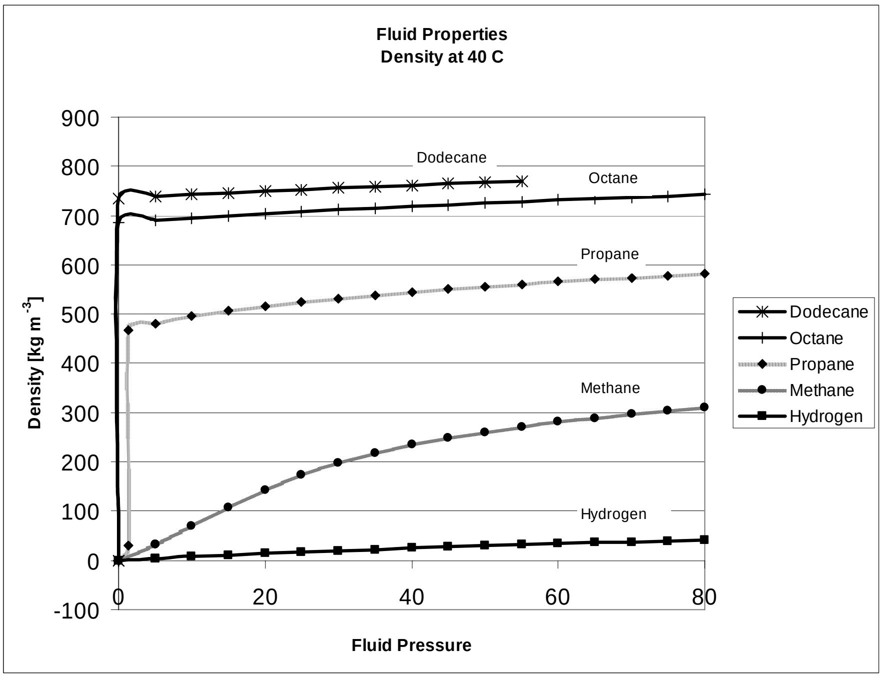


Figure 12 – Density vs. Fluid Pressure (at 40 °C)

It is also noteworthy that, for the same chemical energy flowrate, in theory, a hydrogen injector must increase the most restrictive internal flow passages as compared to a similar natural gas injector. This can be achieved, with higher needle lift (+ 24%) and larger spray holes (+ 12 % diameter). In practice, it was found that an existing natural gas injector could be used to develop the J43Px family. In the highest flowing natural gas injector (model J43P3), a larger actuator was used to increase needle lift to meet technical requirements.

Fluid Density & Damping

The fluid density of hydrogen is roughly 1/50 that of diesel fuel at 25 MPA pressure (typical maximum operating pressure). This means that damping effects due the fluid density and velocity is greatly reduced with hydrogen. Careful control of the needle opening strategy with the electronic driver is required to protect against resonant effects. Severe resonance can lead to momentary physical separation of the needle/ hydraulic compensator/ piezoelectric actuator. This can cause high tensile forces in the actuator and cracking of the ceramic material. Although the injector needle can be opened in less than 100 µsec, in practice the injector uses a more gentle opening profile which is about 300 µsec.

Finally, when the needle closes, careful control of the actuator / needle is also required. Ideally, for combustion reasons, it is best to close the needle quickly while avoiding high impact velocities which can cause needle bouncing. In fact, piezoelectric control methods allow for variable position and velocity control. The present injector design uses direct coupling between the needle and actuator which allows one to can take full advantage of these features. Full “shaping” of the needle opening or closure profile is limited to some degree by the physical and computation limits of the present electronic driver. It is normal practice to close the injector quickly (perhaps at about 1 m/sec or less) and then further decelerate the needle just before it seats by momentary slowing the needle with “hold” pulse just before seating.

Fluid Viscosity

In diesel injection technology, fluid viscosity is a very important parameter. In fact, for diesel fuel, the acceptable viscosity range is defined at 40 ºC to be between 1.1 cP and 3.4 cP (1.3 to 4.1 cSt) for 1-D and 2-D grades of diesel (per ASTM D975).

The J43 injector used for direct injection of hydrogen uses similar hardened base materials to diesel injectors. As can be seen in figures 13 and14, the dynamic viscosity for hydrogen is 2 orders of magnitudes lower than diesel fuel (dodecane is used as a surrogate fluid for comparison purposes).

When the needle does seat, there is another effect described in lubrication theory which is known as the squeeze film. As one surface approaches another, the fluid layer in between is squeezed out. This in turn builds up a pressure which helps decelerate the parts, reducing final impact velocity. However, this effect is a function of fluid density and the fluid viscosity. As can be seen in figures 13 and 14, hydrogen’s viscosity is about 100 times lower than diesel fuel (dodecane is a surrogate for diesel fuel). Combined with its lower density, the squeeze film effect is greatly reduced. Metal-to-metal contact will occur at higher energy levels than with a liquid. This can lead to higher wear rates. Velocity control becomes an even more important mitigation method for this reason. As well, special coatings which can reduce adhesive wear at a microscopic level could help greatly. The exact magnitude of the problem will require further study with an accelerated test mythology.

These cumulative effects from low density and low viscosity drive the need for specialized dry lubricants or ultra-low friction / low wear coatings, as will be seen later.

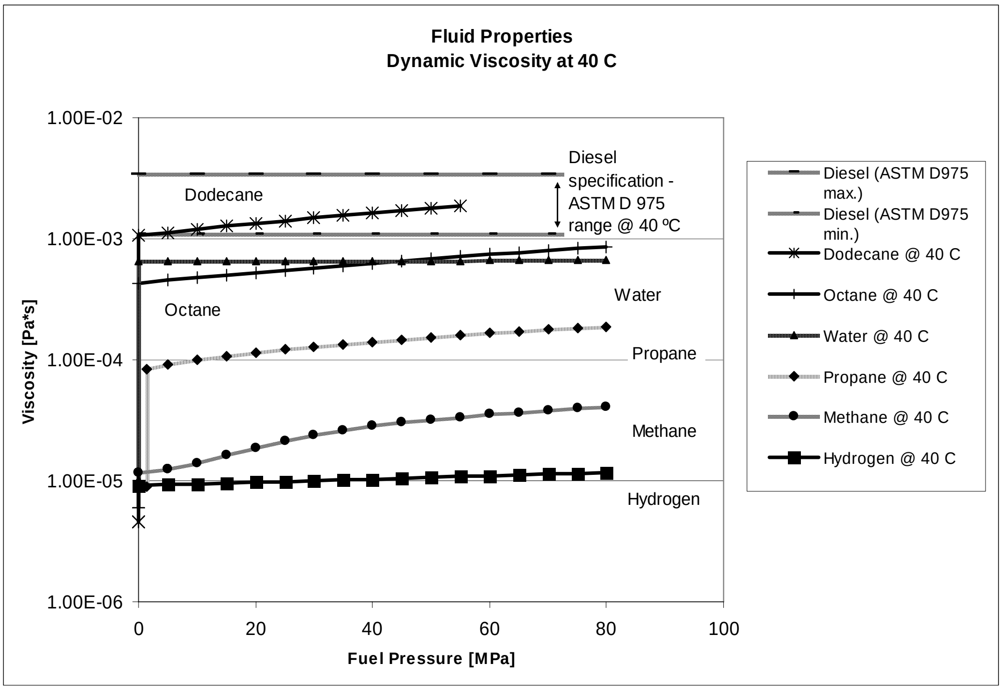


Figure 13 – Viscosity vs. Fluid Pressure

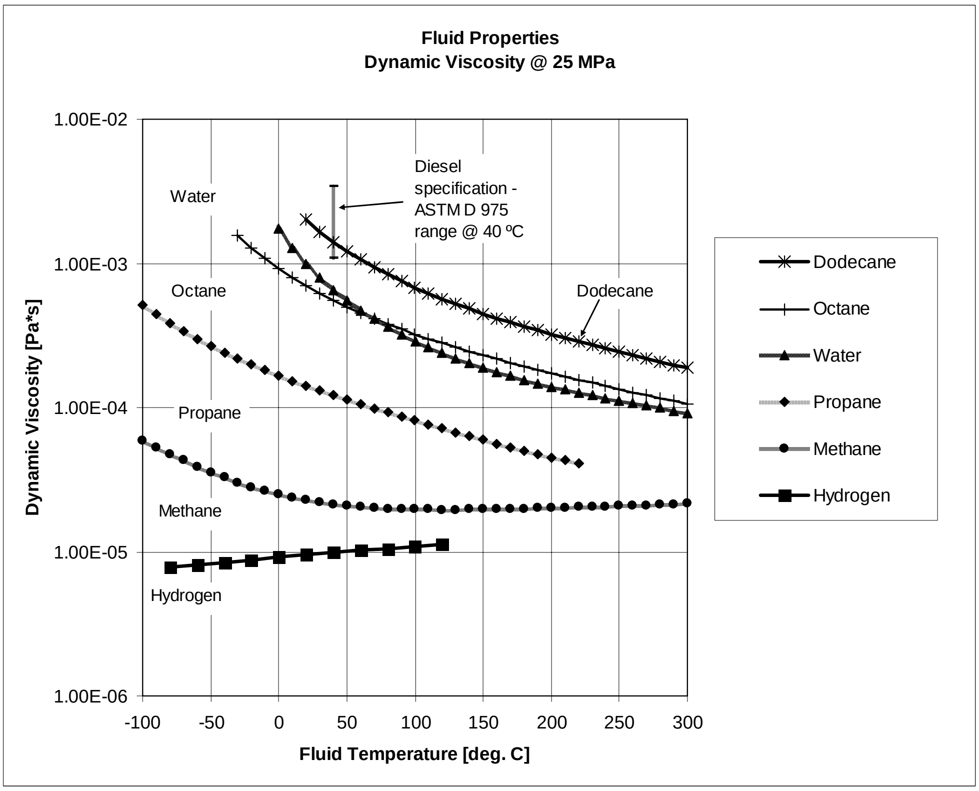


Figure 14 – Viscosity vs. Fluid Temperature

Implications for J43 Injector Function and Durability

The J43 injector design has been demonstrated to be a useful research tool for early stage single cylinder developmental engines. Higher flow rates achieved with the J43P2 and J43P3, as compared to a previous solenoid based injector [3] (2 g/sec flow at 100 bar), made these piezoelectric injectors attractive for single cylinder engine research. As well, the ability to vary needle position by changing the charging voltage strategy to the piezoelectric actuator has provided the ability to evaluate the effect of multiple injections and different peak flow rates and on combustion.

However, hydrogen's fluid properties described above have created some unique technical challenges for obtaining long term durability. For reference, at an average engine speed of 2000 rpm and 1 injection per combustion cycle, an injector must function without significant degradation for 600 million cycles on an engine designed for a 10,000 hour durability level. If the combustion strategy uses two injections per combustion event, then the required target life (with high probability) is 1.2 billion cycles.

Currently, we have demonstrated the basic opportunity for low emissions / high efficiency / high power density operation with hydrogen direct injection engine technology. The J43Px injector family is viewed as only a research injector at this stage and needs improvements in several areas, to allow future application to multi-cylinder engines or demonstration vehicles.

Fundamental research on material-related wear or failure mechanisms in the injector are now underway and possible technical solutions can also be evaluated. Benefits of new material solutions can be tested first and ranked in a laboratory environment (PNNL), then on a specialized injector test rig (Westport) and finally in an actual engine (Ford).

Discussion below on the injector challenges (figure 15) is separated into 4 areas:

1. Impact related wear at needle/seat interface.
2. Sliding wear between lower needle and nozzle/guide surface.
3. Hydrogen diffusion into dielectric coating or piezoelectric actuator.
4. Seal integrity in hydraulic compensator.

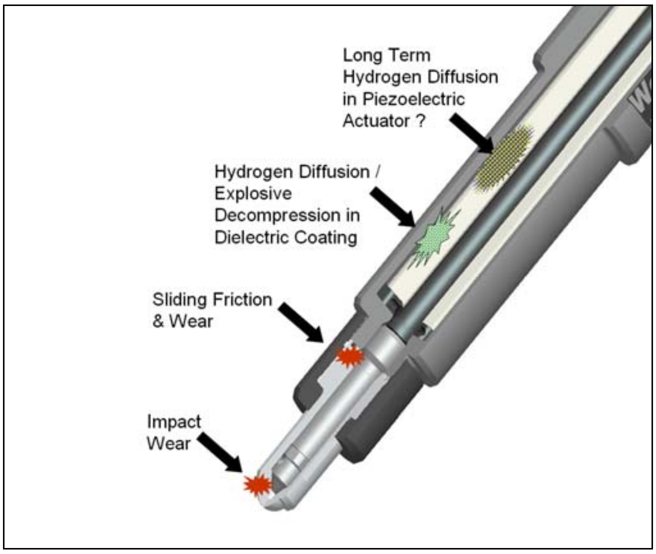


Figure 15 - Key Technical Challenges

4. Injector Status and Future Research

Impact Wear at Needle / Nozzle Seat

When the injector needle opens and then closes, the seat and needle do experience a small amount of wear. Upon close analysis, the needle/seat interaction is actually one of sliding impact as the needle contacts the nozzle. Some kinetic energy is dissipated at the contact points due to elastic compression and shear at the surface of the materials. During break-in it has been observed the contact patch will experience some plastic deformation until reaching equilibrium. Typically the contact patch is an annular ring with has a nominal width of 250 microns.

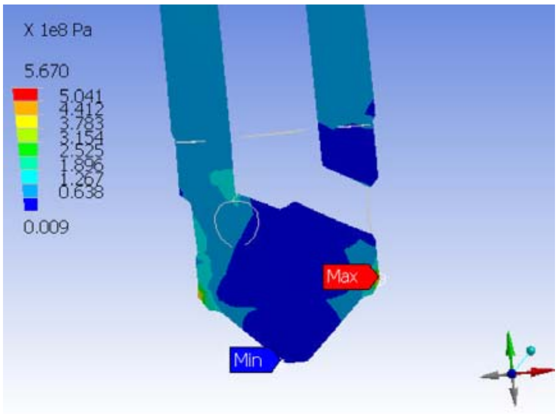


Figure 16 - Stress Contours in Needle Tip With 2000 N Axial Load

Figure 16 shows an example of stress analysis used to understand the effect of impact on the needle which is made of a hardened tool steel. This example shows that for a peak impact force of 2000 N (based on elastic energy considerations in system) that the needle sealing surfaces approaches 500 MPa compressive stress (which is 15% of the material's yield stress).

Apparent wear rate at the needle seat interface with the J43Px injector is considered to be low. However, occasionally, leakage has been observed due to particles in the gas stream or slight surface damage after 1 to 10 million cycles.

In future PNNL studies, a test set-up will be used to model sliding impact based upon empirical data. Using higher needle closing velocities may also be useful as an accelerated testing methodology on an injector test rig at Westport or in a Ford engine.

As well, new coatings suitable for impact are being considered at PNNL. Initial evolution in a laboratory environment will be followed by application to injector needle tips. In the near future, we will be conducting tests on nanolaminate combinations, diamond-like carbon coatings, and bare metals that have been exposed to high pressure hydrogen. From these studies, we anticipate further understanding of the effect hydrogen has on the embrittlement of materials in the H-ICE service environment.

Finally, improved injector velocity control algorithms with the electronic driver can further reduce the needle closing velocity. Wear predictions based on the impact energy will be used for assessing durability potential and provide confidence that technology improvements are substantial.

Dry Siding Wear with Needle / Nozzle Guide

The needle in figure 15 is very precisely guided by the upper cylindrical surface on the nozzle. Using special honing and matching techniques, the nominal clearance is only 2 microns (radial). Both the needle and the nozzle used hardened tool steels of different compositions. Furthermore, the needle uses a commercial protective coating with very high hardness to protect against galling which was seen earlier in another injector design (solenoid type). To date, there has been no evidence of galling but the coating (applied to the outside of the needle) only has a relatively low friction coefficient (μ = 0.1 to 0.2). Other coatings exist which may be more suited the hydrogen environment and have much lower friction coefficients and wear rates.

Research on candidate coatings (very low friction, dry films such as various diamond-like carbon formulations) is being pursued at PNNL in collaboration with Argonne and some industrial suppliers as well. PNNL has developed two dedicated high pressure autoclaves (figure 17) for performing friction/wear studies with a special reciprocating pin-on-flat test rig in hydrogen. The autoclave is also used look at hydrogen diffusion issues in various materials.

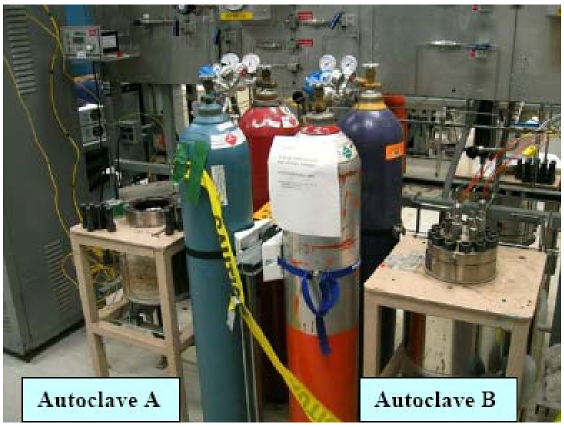


Figure 17 - PNNL Autoclave A and B (1 to 300 bar, 20 C to 300 C)

The friction and wear characteristics of metallic materials depend upon several factors, including material conditioning, environment, lubrication, and in the case of many materials, the growth of surface oxide films. Within a hydrogen service environment, which by definition is chemically reducing so that the loss of the surface oxide by wear will result in bare surface contact, the result is an increase in friction and wear. Additionally as described above hydrogen has very low viscosity – so that any hydrodynamic effects are minimal when parts are in motion, however brief.

Candidate needle-nozzle materials have been exposed to hydrogen under various conditions to better understand the diffusion mechanisms involved; others have been exposed to high-pressure hydrogen and subsequently tested a in reciprocating hydrogen environment. It is interesting to note that even this limited amount of data indicates that the hardness of the certain materials increases measurably depending upon the test depth as a function of pre-test exposure time to hydrogen (up to 1000 hours has been studied).

Reciprocating pin-on-flat tests of both hydrogen exposed and unexposed samples has been conducted and is in process. Early trends have been observed:

1. The hardness of certain tool steel materials appears to be slightly higher than that of the non-exposed samples.
2. Tool steel alloy elements are the biggest single factor determining the effect of hydrogen.

3. Previous hydrogen exposure does have an effect on frictional behavior. It appears beneficial for steels tested in argon but had mixed influence in air due to the oxidation environment. Different wear modes were observed; oxidized-wear dominating in air and abrasive-wear dominating in argon.
5. New accelerated life tests are being devised to both expose samples to high pressure, high temperature hydrogen and to rapidly predict end-of-life properties of material combinations for special injector test rig or engine tests.

Actuator Robustness (Effect of Hydrogen on the Dielectric Coating and Piezoelectric Material)

The actuator, itself has been observed to be a source of some potential failures or aging mechanisms as well. They can be basically divided into 3 categories:

1. Actuator cracking due to unwanted tensile loads.
2. Failure of dielectric coating and short circuits between adjacent electrodes.
3. Deactivation of the actuator material.

Actuator Cracking

Cracking of the actuator has been observed if the components are not properly aligned due to assembly or part geometry not being at nominal values. Misalignment can introduce a bending moment of the stack and this in turn can lead to unwanted tensile forces in the piezoelectric material (PZT[4]). Careful attention to cleanliness, design tolerances and features which assure component alignment have largely eliminated this failure mode.

Delamination / Explosive Decompression

Another failure mode that is sometimes observed, but is now better understood is the appearance of bubbles and consequent delamination of the epoxy coating used on the piezoelectric stack. Testing in the PNNL autoclave has shown that the epoxy material is prone to hydrogen diffusion and then decompression damage (figure 18) afterward when the pressure is relieved. Through study of epoxy samples, it was found that the material was probably not fully cured, nor was it suitable once cured and the glass transition temperature ($T_g < 60$ ºC) was far too low for our application. Failure of the epoxy can then also lead to voids and micro-arcing and carbon tracks which can create an electrical short between adjacent electrodes in the stack, effectively causing it to stop functioning properly.

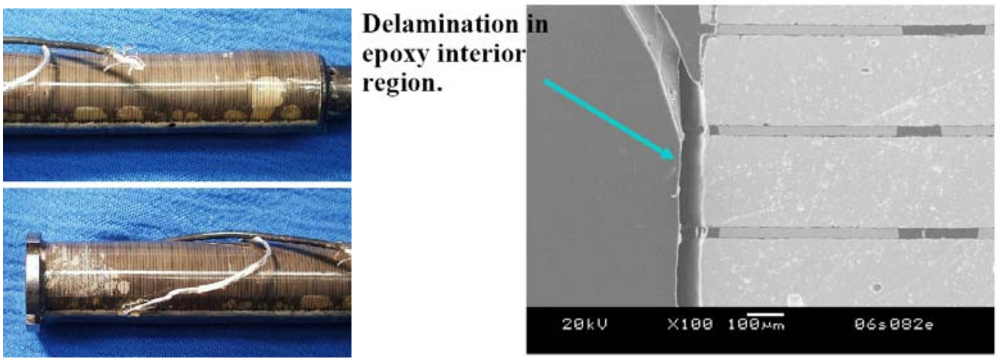


Figure 18 –Damage (lighter regions) to Epoxy Dielectric Layer on Piezoelectric Actuator (left) and Close-up of Epoxy Dielectric Coating which has Delaminated (right)

[4] lead zirconate titanate ($Pb[Zr_xTi_{1-x}]O_3$, $0<x<1$)

Deactivation of the Piezoelectric Material

The role of hydrogen in deactivation of PZT is not clear at present. Piezoelectric devices in hydrogen undergo hydrogen permeation into the lattice and subsequent electrical property degradation due to changes in internal dipole moments within the crystal from the formation of OH^- bonds. However, this particular degradation mechanism did not occur for these actuators to a significant depth, as the failure seems to be due to surface corona discharge (apparent short circuits). Further testing and analysis may be required to understand this degradation process and to determine the overall reason for the surface discharge that occurs.

It is interesting to note that the negative copper electrodes (normally bright) darkened during this testing, while the positive electrodes remained bright. Further tests are required to identify this darkening process and apparent chemical change at the negative electrodes.

Seal Leakage in Hydraulic Compensator

The hydraulic compensator utilizes several static and dynamic seals to contain the hydraulic fluid inside. Some issues with infant mortality have been experienced due to assembly errors in which, o-rings can be nicked or cut, causing fluid leakage and loss of needle lift. These types of problems will usually appear in 10 or less hours of operation. Careful assembly procedures can avoid these issues. However, in the long term, some changes to the design features and assembly method may be made to eliminate the root problems.

The other known issue involves differences in coefficients of thermal (CTE) which manifests itself in different rates of expansion. Because the hydraulic compensator is a closed system, the commercial hydraulic fluid will expand more than the metal parts at high ambient temperature conditions. This causes the trapped fluid pressure to increase which in turn displaces seals and may cause some damage. However, in practice, this issue is very difficult to model or replicate on a test bench because minute differences in dead volume of the final assembly can greatly affect the peak pressure. Hydraulic compensators of similar design have survived for over 900 hours in CNG injectors without failure. And some hydraulic compensators have experienced more than 200 hours operation on hydrogen with no problems, after which the injectors have been rebuilt for another test.

Future work will focus on dealing with improved assembly and fundamental evaluation of the seal integrity and the thermal expansion issue. Much of this will require the use of a dedicated hydrogen fuelled injector test rig. Accelerated test methods will be used to force failures and improve our understanding of these issues. Some existing, yet untested design concepts for mitigating these issues are being considered too.

5. Conclusions

A second generation hydrogen direct injection technology (fully electronic / direct acting) has been developed which provides desired performance (opening speed, repeatability, and peak flow rate with multi-injection capability) for ground-breaking engine research. Engine research activities at Ford have demonstrated excellent efficiency (45%, brake thermal efficiency) which meets the DoE FreedomCAR goals for 2010 [5]. Power density is superior to the port injected approach. NO_x formed at moderately high temperatures in-cylinder, the only significant emission, can also be effectively managed through a combination of early and late cycle injection strategies.

Fundamental materials research has been essential in defining certain failure mechanisms in the hydrogen injector sub-components and has also directed us toward several potential solutions. Evaluation of new materials in injectors will provide further insight.

The main near term development goal is to substantially decrease injector life from about 200 hours to 1000 hours. This would allow the development and demonstration of an early stage multi-cylinder engine with advanced features and material technology integrated in the direct injection fuel system. A longer term goal is to perhaps develop and prove 10,000 hour level durability through further materials research, accelerated testing on injector rigs and full scale engine testing.

6. Acknowledgements

The authors would like to thank the following organizations and individuals for their support and contributions:

- Department of Energy (FreedomCAR), Oak Ridge National Laboratories, Argonne National Laboratories, Sandia National Laboratories, and Natural Resources Canada (CTFCA).
- Within Ford: Matthew Younkins, Howard Jung, Erik Cross, James Larcom, William Stockhausen, August T. Vaught, George Papaioannou, Curtis Potts, and Kathy Barrett.
- Within Westport Innovations Inc.: Mohammed Tahir, Charlie Loo, Mike Hebbes, Patric Ouellette.
- Within PNNL: Chuck Henager, Stan Pitman, Joe Ryan and Wendy Bennett

7. References

1. Xiaoguo Tang, Daniel M. Kabat, Robert J. Natkin and William F. Stockhausen, Ford Motor Co., James Heffel, “Ford P2000 Hydrogen Engine Dynamometer Development”, SAE 2002-01-0242; 2002

2. Andreas Wimmer, Thomas Wallner, Graz University of Technology; Jurgen ringler, Falk Gerbig, BMW Group Research and Technology; “H2 Direct Injection – A Highly Promising Concept”, SAE 2005-01-0108; 2005

3. David Mumford, Alan Welch, Bernd Bartunek: “Development of H2 Direct Injection Technology for High Efficiency / High BMEP Engines”, 1st International Symposium on Hydrogen Internal Combustion Engines, September 28-29, 2006, Graz, Austria.

4. John B. Heywood, “Internal Combustion Engine Fundamentals”, McGraw-Hill, Inc., 1988.

5. National Research Council of The National Acadamies, “Review of the Research Program of the FreedomCAR and Fuel Partnership – First Report”, The National Academies Press, 2005.