Natural Gas injection for low CO$_2$ spark ignition engines

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Abstract: Compressed natural gas is increasingly being considered as a vehicle fuel due to its low CO$_2$ impact and its growing global availability at an attractive price. The current state of the art for light duty compressed natural gas (CNG) engines in series production is port fuel injection (PFI). In downsized, boosted engines this results in a loss of low-end torque when compared to a gasoline direct-injected (DI) engine due to lower volumetric efficiency and the inability to perform scavenging.

One method for recovering this torque loss is direct injection of the gaseous CNG fuel. Significant progress has been made in the development of direct injection of compressed natural gas for passenger car engines. The key enabling component is the DI-CNG injector, for which the concept and the development status will be presented. The next Delphi project phase will focus on process development and the conception and installation of a prototype assembly line in order to prepare the future industrialization of the CNG injector hardware. These activities are supported under the umbrella of a European LIFE+ project.

Additionally, engine and vehicle benefits will be summarized showing the ability to meet and even exceed current downsized DI-gasoline performance.

Keywords: Alternative Fuels, Compressed Natural Gas, Direct Injection.

1 Introduction

CNG offers an attractive path to reduce CO$_2$ and particulate matter emissions. Today’s CNG engines in series production use manifold port fuel injection of the gaseous fuel. The injection of gas into the manifold reduces the amount of oxygen in the cylinder and results in a loss of low-end torque compared to a gasoline direct injection (GDI) engine. The lowered volumetric efficiency and the inability to perform scavenging diminish downsizing capability in comparison to modern boosted GDI engines.

The low-end torque loss is noticeable to customers, both in the engine performance specifications and in the resulting vehicle on-road drivability.

While alternative solutions to increase low-rpm torque exist (e.g. larger displacement engine, multi-stage boosting, etc.) they have a significant negative effect on cost, packaging and weight.

The direct injection of compressed natural gas (DI-CNG) technology overcomes the limitations of CNG PFI as the gas can be injected into the cylinder after the closing of the intake valve. Greater downsizing is possible and an equivalent driving performance can be maintained in comparison to GDi engines.

Furthermore, the direct injection approach allows the engine fuel conversion of existing GDi applications by replacing the GDi injector by a package compatible DI-CNG injector.

This paper discusses the progress of the DI injector system development at the Delphi Customer Technology Centre Luxembourg. Selected engine and vehicle implementation results will be presented and finally the further development plan will be outlined.

2 CNG as an automotive fuel

2.1. Rationales for CNG

While the technology and system architecture remain similar to gasoline injection, CNG offers the highest hydrogen to carbon ratio of all fossil fuels, including LPG. As a consequence, CNG powered cars offer about 25% lowered CO$_2$ emissions compared to equivalent gasoline powered vehicles. Also, results show that CNG powered engines produce significantly lower particulate emissions.

In terms of combustion, the higher octane number of CNG allows increased compression ratios. Finally, CNG has a future sustainable alternative in biomethane.

Figure 1: Light duty Natural Gas Vehicle market [1]
Estimates of the CNG market show steady growth in the light duty truck and passenger cars segments (Figure 1). Challenges for future growth are the currently low vehicle range due to the size and pressure limitations of current gas tanks, the limited refuelling infrastructure and the uncertainties and regional variation of tax regulations.

Today already a large variety of CNG cars exists [2]. These CNG applications are equipped with port fuel injectors. As a response to this growing market, Delphi has developed the Multec\textsuperscript{®} 3.5 CNG Port Injector (Figure 2).

![Figure 2: Delphi’s Multec\textsuperscript{®} 3.5 CNG Port Injector](image)

The main feature is an elastomeric seal with high durability and near-zero leakage. The elastomeric seal has been preferred to a traditional “hard/hard” valve/seat seal, in view of the robustness to wear and the expected difficulty to achieve the target leak specification when dealing with a gas.

The injector also uses a high-force coil and specially selected internal materials and surface coatings to enhance durability in the non-lubricating CNG fuel. The injector envelope is compatible with existing PFI applications, and the injector driver uses common and cost efficient “saturated switch” electronics.

CNG's inherent lack of lubricity and the combustion process increased moisture content create important challenges for the fuel injector’s design, performance and durability. Moreover the required gas flow rate is significantly more difficult to achieve with CNG than with liquid injection.

The high level specification of the injector is shown in Figure 3 below:

![Figure 3: PFI main injector specifications](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CNG Port Injector Specification (Standard Flow)</th>
<th>CNG Port Injector Specification (High Flow)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. Operating Pressure</td>
<td>9-bar absolute</td>
<td>9-bar absolute</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>(-30^\circ\text{C} \text{ to } 125^\circ\text{C})</td>
<td>(-30^\circ\text{C} \text{ to } 125^\circ\text{C})</td>
</tr>
<tr>
<td>Max. Flow @ 8-bar CNG</td>
<td>2.4 g/s</td>
<td>3.1 g/s</td>
</tr>
<tr>
<td>Tip Leakage Max. [420kPa N.L.]</td>
<td>(\leq 0.10 \text{ ucm})</td>
<td>(\leq 0.10 \text{ ucm})</td>
</tr>
<tr>
<td>Minimum Opening Voltage</td>
<td>(\geq 7.5V)</td>
<td>(\geq 7.5V)</td>
</tr>
</tbody>
</table>

2.2. Challenges of PFI and DI answer

The PFI CNG injection technologies are challenged by a low end torque causing reduced drivability compared to current technologies (Diesel and gasoline).

The reason is the manifold injection itself and the reduced volumetric efficiency. Injecting the gas in the intake manifold reduces the maximum amount of air that is available for the cylinder filling. Scavenging is also limited since gas would be directly flowing to the exhaust.

Direct injection is a solution to recover the loss of volumetric efficiency of the port-fuel injection technology. The gain of vehicle performance, primarily in terms of torque at low engine speed will increase public acceptance of the CNG injection technology.

3 The Delphi DI-CNG injector

3.1. CNG Direct Injector High Level Requirements

The DI-CNG vehicle concept of tomorrow is largely built on the system architecture of today’s production CNG vehicles. The design and development of the injector system was driven by the primary requirements:

- Applicability to passenger car engines, downsized and boosted, in line with the current gasoline engine trends
- Compatibility with existing gasoline injector packaging envelopes: an easy exchange of injectors favors conversion to CNG from existing gasoline engines with fewer required modifications
- Maximize the vehicle driving range for end-user acceptance in the market
- The ultimate technology goal is to exceed the torque and power of the gasoline version of the engine.

Based on these high-level criteria, the following injector-level requirements were established:

![Figure 4: DI-CNG main injector requirements](image)
The maximum operating pressure was the result of a compromise between contradicting factors: power is increasing with pressure while vehicle driving range and tip sealing are improving when lowering it.

3.2. Design considerations

The design of an injector for direct injection of CNG comes with specific challenges: (1) low power density carburant: high flow area required to meet the power target, (2) low lubricity of gas: increased wear rate vs. fluid fuels, (3) a higher leakage risk.

The first design features to be selected were the actuator technology and the valve type.

The actuator choice had to be made between the two most standard injector actuation technologies: an electromagnetic solenoid actuator or a piezo-electric actuator.

Clearly the solenoid actuator is favourable according to the Pugh analysis below (Figure 5):

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Solenoid</th>
<th>Piezo-electric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large pintle lift (meet flow)</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Long pulse widths (meet flow)</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Delphi technical re-use</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Small fuel quantity delivery</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>Thermal compensation complexity</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Cost</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>0</td>
<td>(5) + (1) +</td>
</tr>
</tbody>
</table>

Figure 5: Actuator technology: Pugh analysis

The choice of valve type had to be made between inwardly-opening, the standard concept for today's GDi applications, and outwardly-opening.

The primary consideration for the design selection has been the differential pressure acting on the injector valve. This pressure difference is totally different between liquid and gaseous fuel applications.

In gasoline, the fuel pressure is typically higher than the maximum in-cylinder combustion pressure (>100 bar). In CNG applications, the target fuel pressure is substantially lower (<20 bar) in order to maximize vehicle range. This results in higher combustion peak pressures than the fuel pressure and could lead to an opening of the inwardly-opening valve type. In contrast, an outward-opening valve is naturally sealed by higher cylinder pressures (see Figure 6). Therefore the outwardly-opening valve was selected as a baseline for the DI-CNG injector development activities.

16 bar peak gas pressure inside injector

Cylinder pressure > 100 bar peak firing pressure at high load

Figure 6: Inwardly and outwardly opening valves at high load

3.3. Hardware design and build

Several generations of DI-CNG injector hardware have been designed, built and tested. Constant refinement and improvement has taken place in each generation, guided by computational fluid dynamics (CFD) simulation, finite element analysis (FEA) and mechatronic simulations. The fourth generation of the injector, achieving a high level of performance and durability, is shown in the figure below. The requirements as described previously: 7.5 mm tip diameter with a body diameter less than 21 mm and compatibility with today's GDi engine applications, are met.

Figure 7: The 4th generation DI-CNG injector

4 Laboratory test and validation

The performance of the prototype injectors have been assessed in terms of flow delivery and injector tip leakage both from a part to part and durability robustness point of view.

The flow curves in Figure 8 demonstrate the flow capability of the current injector generation hardware at 6 and 16 bar fuel pressures.
DI-CNG injectors were tested to product lifetime using dry CNG as test fuel.

The graph below shows that the flow delivery of each injector at 7 ms remained within the defined limits of their initial value.

Injector sealing has been the most challenging target. Figure 10 below shows the progress in meeting the target near zero leak values over several injector generations. The development included the optimization of materials and surface conditions as well as design improvements on the valve group and seal interface geometry.

The current generation (Gen 4) injector has met the leakage requirement over its entire product lifetime during bench durability test cycles (Figure 11).

During the course of the project, prototype injectors have been made available for evaluation in several engine environments. These include testing in a concept car made by Magna Steyr in association with TU-Wien [3], as well as by OEMs including Ford and Daimler who published results at the 23rd Aachen Colloquium, 2014 [4].

The Aachen publication highlights results from experiments conducted using current production engines converted to DI-CNG. The injectors were mounted in a central cylinder head position replacing the GDi gasoline injectors (see the example in Figure 12).
Both Daimler and Ford demonstrated the potential of the DI-CNG technology in terms of low-end torque improvement compared to PFI (see the example in Figure 13). The achieved level of performance was similar to today’s GDI applications [4].

During engine testing at Daimler, the Gen 4 DI-CNG injectors have proven their durability in a number of tests. Single injectors reached a running time of 2,000 hours corresponding to a third of lifetime assuming an average engine speed of 2500 rpm. In total, the run time of Gen 4 DI-CNG injectors at Daimler sums up to more than 20,000 hours. A demanding endurance test of over 1,000 hours duration was passed by all injectors. The prototype engine with CNG direct injection was installed in a current Mercedes-Benz B-Class natural gas test vehicle for mono-fuel operation (B 200 NGD, Figure 14). Good and robust operating performance was observed in conjunction with increased performance and drivability.

In addition to the CO₂ benefit, natural gas engines also produce very low particulate matter exhaust emissions. A comparison of particulate number (PN) vehicle emissions in the NEDC test cycle show that natural gas vehicle emissions, with PFI or DI, are more than an order of magnitude below the legislation limit and produce substantially lower number of particles than the gasoline application.

6 Next injector development steps

The current Gen 4 injector design is an advanced laboratory prototype. The manufacturing process is highly manual and is intended for technology demonstration. The focus in the next phase is the development of manufacturing processes and industrialization strategies in order to bring the injectors to a marketable stage.
The DI-CNG injector industrialization development is supported by LIFE+ [5].

LIFE+ is the European Union’s funding instrument for the environment and climate action. The general objective is to contribute to the implementation, updating and development of EU environmental and climate policy and legislation by co-financing projects with European added value. The LIFE DI-CNG project finances the testing, prototyping and demonstration phases, meaning the development and validation of a technology at pre-industrial stage. Production-intent DI-CNG injectors will be developed for equal or better low-end torque than comparable DI gasoline and Diesel engines, leading to improved driving performance and end consumer acceptance.

7 Conclusion

The 2020 and 2025 CO₂ targets require dramatic improvements in powertrain efficiency. Several European strategy papers encourage growth of CNG vehicles as strong contributor for regional environmental policy, climate change and crude oil independence.

CNG is one sustainable solution to reduce CO₂ compared to gasoline engines, with a path to sustainability with bio-methane. Through direct injection, CNG as a fuel becomes an attractive alternative in terms of fuel consumption, driveability and emissions.

Delphi successfully developed R&D injectors, used by partnering OEMs to demonstrate the potential of the technology at the engine and vehicle level. The injector developed by the Advanced Powertrain team at Delphi has met the defined flow and leakage targets. Lifetime durability has also been demonstrated on a small quantity of injectors at the laboratory level. Injector testing experience on an engine is very positive in terms of performance and durability.

The future will depend on factors such as filling station footprint and tax regulations at European and regional levels. Delphi will transition in its next development phase, from R&D to production-intended solutions, enabling the technology to be marketable at the end of project.

8 Acknowledgement

The authors would like to thank Daimler and Ford for their support of the DI-CNG injector technology development at Delphi and the ability to share engine results in this paper.

9 References


10 Glossary

CNG : Compressed Natural Gas
DI-CNG : Direct Injection- Compressed Natural Gas
PFI : Port Fuel Injection
NGVA : Natural and bio Gas Vehicle Association
GDi : Gasoline Direct Injection