Highly Efficient Natural Gas Engines

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Abstract

The 2020+ CO_2 and regulated noxious emission limits will impose drastic technological choices. Even though in 2030 65% of road transportation vehicles will be still powered by internal combustion engines, a progressive increase of hybrids and battery electric vehicles is expected. In parallel, the use of low-carbon alternative fuels, such as natural gas/ biomethane, will play a fundamental role in accelerating the process of de-carbonization of the transportation sector supporting the virtuous circular economy.

Since the nineties FCA has invested in CNG (Compressed Natural Gas) powered vehicles becoming leader with one of the largest related product portfolios in Europe. A progressive improvement of this technology has been always pursued but, facing the next decades, a further improvement of the current CNG powertrain technology is mandatory to achieve even higher efficiency and remove residual gaps versus conventional fuels.

CNG direct injection technology will be a step forward because it can be easily applied on new generation spark ignited engines providing simultaneous benefits in terms of performance (gasoline-like) and engine efficiency (4-6%), particularly in combination with variable valve actuation, advanced boosting, high compression ratio and alternative combustion cycles.

The paper shows a comprehensive overview of this technology evolution, focusing on a related large collaborative project named “GasOn” supported by the EU commission.

Introduction

Natural Gas is a key source for the sustainable mobility and the de-carbonization of the transportation sector [1]. CNG, as an automotive fuel, provides a relevant contribution to clean the environment and mitigate climate change thanks to its clearness in nature and the lowest carbon content among carbon-based fuels.

Moreover the renewable version of CNG, the so called biomethane, can achieve carbon neutral fuel classification if produced by biomass or liquid manure according to the third biofuel specifications [2].

CNG represents an efficient, affordable and immediately available fuel to mitigate pollution problems in urban areas and reducing CO_2 emissions [2].

Since 1990’s CNG shows the lowest cost of ownership among alternative fuels with an adequate driving range and a continuous growth of refueling station [3].

Twenty years of experiences (figure 1) confirm robustness of current technology based on [4]:

- Otto cycle combustion and stoichiometric operation in all conditions
- tailored ignition system (spark plug/coil)
- port fuel injection (sequential multipoint)
- tailored materials (seat valves/valves), 3way catalyst and control strategies
- feeding and storage system with the best in class components in terms of safety.

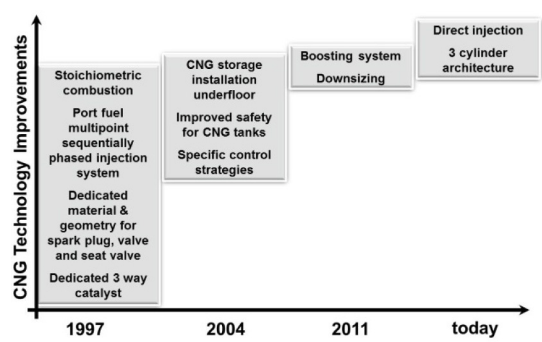

Figure 1. CNG technology evolution

Thanks to these technologies, the recent Euro6 CNG applications provide the following benefits [5]:

- performance improved by means of new boosting system
- reliability and maintenance equivalent to gasoline engines
- CO_2 emissions already compliant with European Union 2020 targets
- fuel tank installation to achieve at least 300 km of CNG driving range plus full gasoline range
- unchanged trunk volume versus gasoline version.

Even if current CNG technology is mature, the goal for the next generation of engines is to develop a technology exploiting all CNG benefits without drawbacks [6]:

- removing performance gap to achieve gasoline-like target
- avoiding installation impact to be compatible with modern direct injection engines
- improving engine efficiency for post 2020 CO_2 challenges.

To achieve gasoline-like performance the basic concept is to remove volumetric efficiency losses due to gaseous port fuel injection by means of technology able to introduce CNG directly into the combustion chamber, after the intake valve closing, to trap the desired air [7].

The challenge is to inject the fuel into the combustion chamber at low pressure avoiding expensive systems to recompress the fuel [8].

To enhance engine efficiency, high compression ratio is considered taking into account the high octane number of CNG [9].

In order to assess the impact of the abovementioned technologies on a quantitative basis, several investigations at simulation and experimental stages were carried out [10], [11], [12], [13]. The novelty of this paper refers to side instead of central direct injection of CNG matched with high compression ratio, boosting and variable valve actuation. To assess the potential improvements of CNG direct injection in terms of air/gas mixing, performance and combustion CNG port fuel injection technology was adopted as reference.

Test Engine and Experimental Setup

The engine selected for the investigation was a 1.4 liter turbocharged, the main features of which are listed in Table 1. The engine was always fueled with a 100% CH_4 (Low Heat Value 50 MJ/kg)

The engine is equipped with a variable valve actuation system already applied on gasoline engine [14], where both intake valves are operated by a unique electro-hydraulic actuator, the operating principle of which can be briefly summarized as follows (Figure 2). The cam is acting on a piston, which is connected to the intake valve through a hydraulic chamber, which is filled by lubricant oil and can be used to couple or decouple the valve motion from the cam profile. The pressure in the hydraulic chamber is controlled by an on/off solenoid valve. The valve closing stroke is controlled by a dedicated hydraulic brake to ensure a soft landing phase. A tailored cam was designed to optimize for the CNG combustion.

Table 1. CNG engine specification

Feature		Metric
Displacement	1368	cm^3
Cylinders	4	-
Fuel type	CH_4	-
Bore	72	mm
Stroke	84	mm
Compression Ratio	13:1	-
Rated power	100	kW
at engine speed	5500	1/min
Rated torque	250	Nm
at engine speed	1500 - 3500	1/min
Air management	Variable valve actuation	
Injection	Port Fuel & Direct	
Boosting	Turbocharger w/ waste gate	

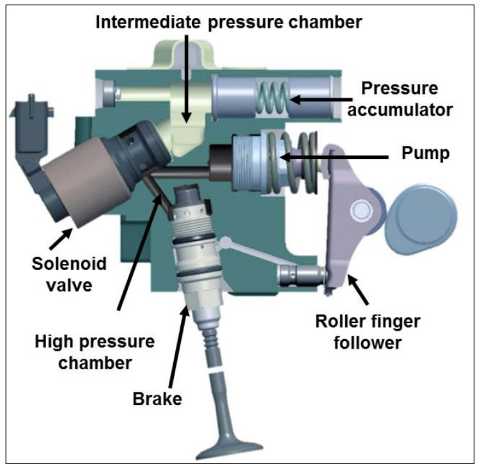

Figure 2. Variable valve actuation system

A new layout (figure 3) was designed to install CNG direct injectors instead of gasoline to perform the experimental investigations on engine at test bench.

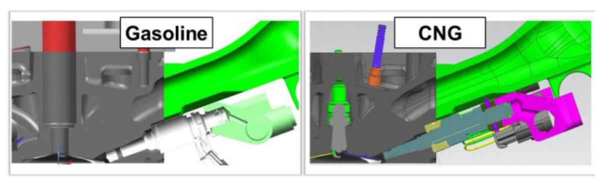

Figure 3. CNG side direct injection layout versus conventional Gasoline Direct Injection.

The adopted CNG direct injector was supplied by Delphi and is based an outward opening valve concept controlled by a peak & hold command.

The main features [15] are summarized in table 2.

Table 2. CNG direct injector specifications

Feature		Metric
Operating pressure	8÷16	bar
Static flow rate	6.7 @ 16bar	g/s
Electric command	peak & hold	-

In details, the injector is equipped with a solenoid and a poppet-like needle valve. At start of injection, the needle protrudes outside the injector towards the engine cylinder, thus detaching from the needle valve seat and opening an annular flow passage. Such annular passage, together with a portion of the injector internal passage upstream of the opening around the needle, is axial-symmetric.

To achieve a precise CNG metering through the injector a choked flow was always executed [16].

The gas through the valve mitigates the temperature of injector tip exposed to the combustion chamber flame. The maximum injector tip temperature detected at engine rated power was below 150 °C far away the maximum allowed value.

The adopted principle of injection is displayed in figure 4 where the start of injection occurs immediately after inlet valve closure and the injection must be ended before the pressure in the combustion chamber exceeds the maximum allowed injection pressure (16 bar absolute).

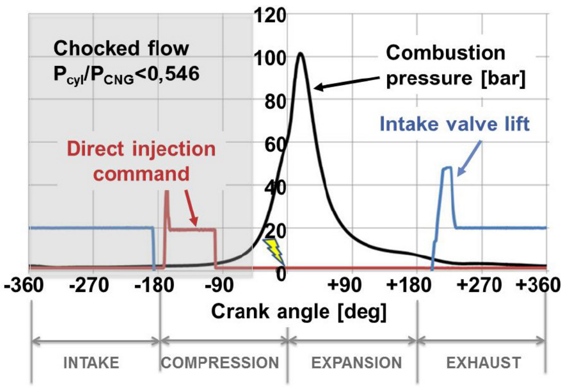

Figure 4. CNG direct injection strategy coupled with Early Intake Valve Closure management.

The combustion chamber was revised on piston shape to achieve a high geometrical compression ratio 13:1, as shown in figure 5.

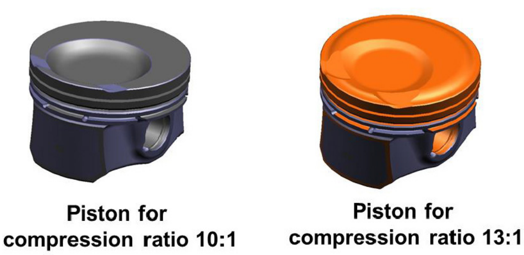

Figure 5. Piston shape for high compression (13:1) CNG direct injection engine versus conventional piston for gasoline (compression ratio 10:1).

The engine was instrumented with four piezoelectric transducers on the cylinder head and coupled with a high-resolution (0.2° crank angle degrees) encoder for in-cylinder indicating analysis as well as a tailored control systems has been set up (figure 6).

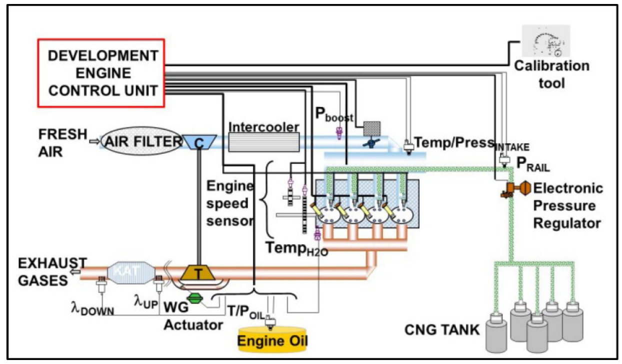

Figure 6. Control system for CNG direct injection

Air/Gas Mixing Simulations

CFD analysis was carried out to understand the air/gas mixing behavior at full and partial load with CNG side direct injection and to validate the design of injector layout onto cylinder head.

A commercial CFD tool [17] was adopted to simulate air/fuel mixing based on a finite volume method (2nd order numerical differential scheme with Reynolds Average Navier-Stokes solver) and standard k-□ RNG turbulence sub-model [18]. The grid adopted is a moving mesh for piston and valves and static for inlet duct and CNG injector.

The cells of the computational grid of the injector are axial-symmetrically distributed forming a cylindrical shape.

Ignition and combustion sub-models were not considered in this work because only air/fuel mixing was carried out mainly to understand the homogeneity of mixture with side injection close to the spark plug suddenly before the ignition event.

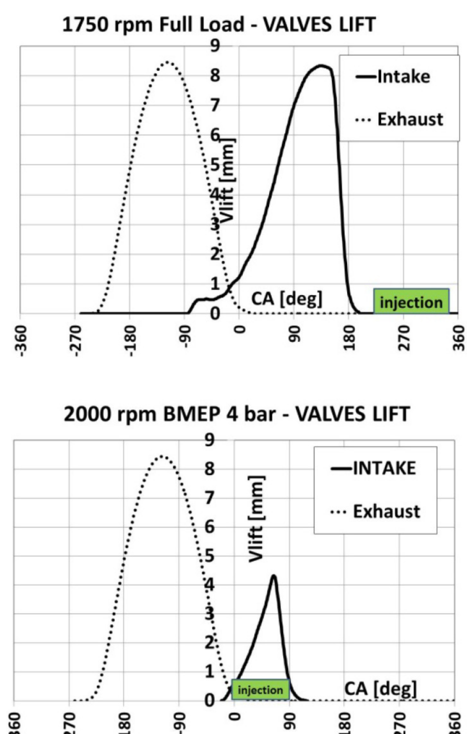

Figure 7. Intake and exhaust valve lift profiles and injection timing

The engine points were selected among the most critical conditions for air/gas mixing (figure 7) during scavenging phase (1750 rpm full load) as well as low load (2000 rpm - BMEP 4 bar).

CFD simulation confirmed that side direct injection of CNG leads to an adequate air/gas mixing close to the spark event (figure 8).

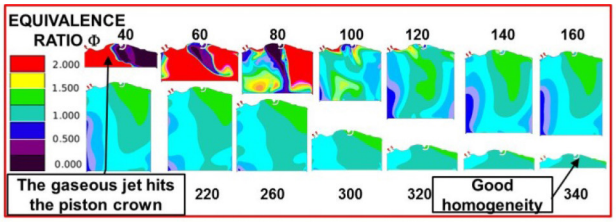

Figure 8. CFD prediction of air/CNG mixing evolution at 2000 rpm - BMEP 4 bar (360 CA means combustion TDC)

CFD prediction shows that approaching combustion top dead center and suddenly before ignition event the equivalence ratio around spark plug is equal to 1 as expected to achieve a stable combustion with CNG mitigating exhaust emissions [19].

Test Matrix

After engine assembly and set up at the test bench, a test matrix was defined to investigate benefits of CNG direct injection vs port fuel injection at full load and the best injection strategy at partial load to achieve the lowest fuel consumption.

The CNG direct injection potential was experimentally evaluated on a test matrix of 50 engine operating points, ranging from 2 to 23 bar BMEP in the speed interval from 1000 rpm to 5000 rpm, as shown in figure 9.

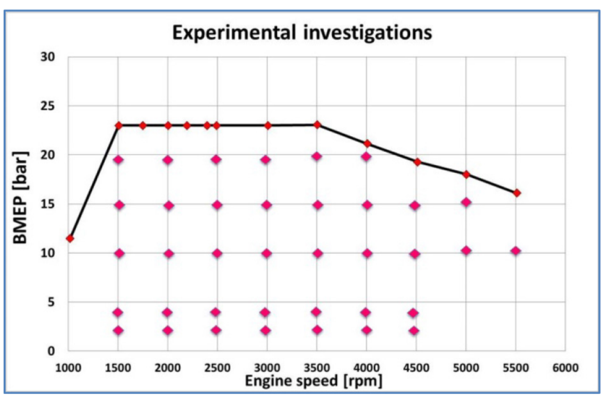

Figure 9. Experimental investigation test matrix

For each engine operating point at full load, the investigation on brake thermal efficiency benefit was carried out without exceeding the following limits:

- turbocharger compressor speed: 240000 rpm
- absolute boost pressure: 2500 mbar
- peak cylinder pressure: 100 bar
- inlet turbine temperature: 950 °C
- outlet intercooler temperature: fixed at 50°C
- lambda: fixed at 1 (stoichiometric) that means air/fuel ratio=17.2.

It is worth to be mentioned that the actuated spark advance was always optimized thanks to the high octane number of 100% CH_4 fuel equal to 130. During experimental tests the knocking phenomena were never encountered.

Moreover, it has to be clarified that load sweeps were carried out always in Wide Open Throttle conditions, achieving the target BMEP level by means of the boost pressure, which in turns was obtained through a suitable setting of the turbocharger waste gate.

Results and Discussion

The benefits of CNG direct injection in terms of performance improvements compared to port fuel injection are summarized in figure 10.

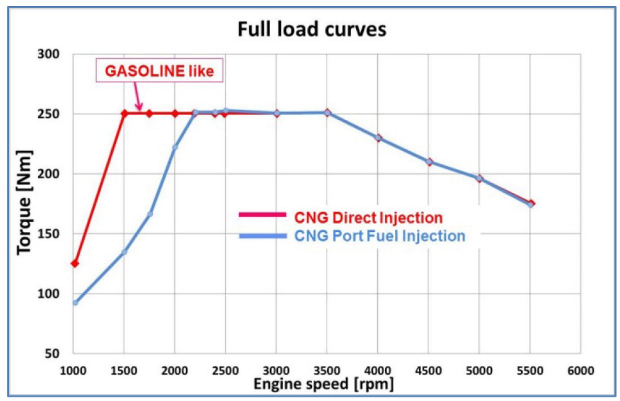

Figure 10. Engine torque of CNG direct versus port fuel injection configurations

As it can be observed, outstanding performance enhancements can be achieved at low/medium engine speeds and full load adopting direct injection rather than port fuel and matching with variable valve actuation system. Direct injection enables the capability to exploit scavenging effect at low engine speed.

As consequence the overall rated torque curve perfectly replicates the gasoline direct injection.

Below 2250 rpm, the performance is achieved with low boost pressure thanks to increase of volumetric efficiency with direct injection versus port fuel injection system (figure 11).

The volumetric efficiency is calculated as the ratio between air flow rate measured versus air flow rate reference.

Another benefit of direct injection refers to faster combustion speed compared to port fuel injection at any engine speed as shown in figure 12.

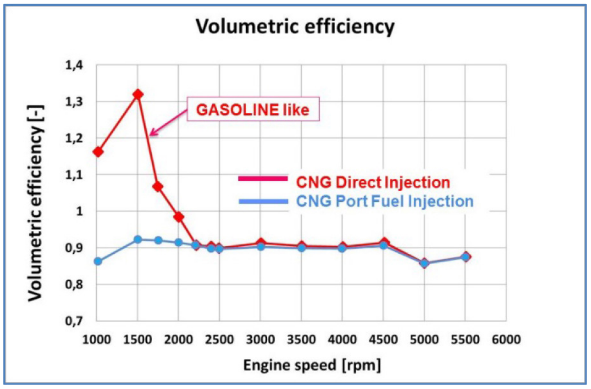

Figure 11. Volumetric efficiency of CNG direct versus port fuel injection configurations at full load

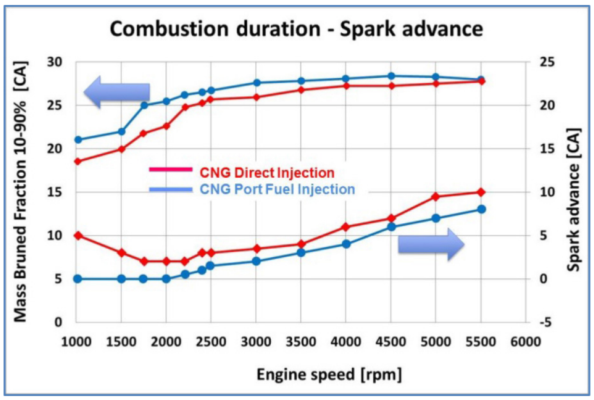

Figure 12. Combustion duration measured as mean fraction burned from 10% to 90% at 5000 rpm full load

With port fuel injection, to achieve the desired low end torque, a retarded spark advance has to be applied delivering the adequate enthalpy to the turbine, increasing combustion duration as drawback.

Moving from port fuel injection to direct injection system the combustion speed becomes faster (figure 13) allowing optimal spark advance and reducing exhaust gas pressure and temperature.

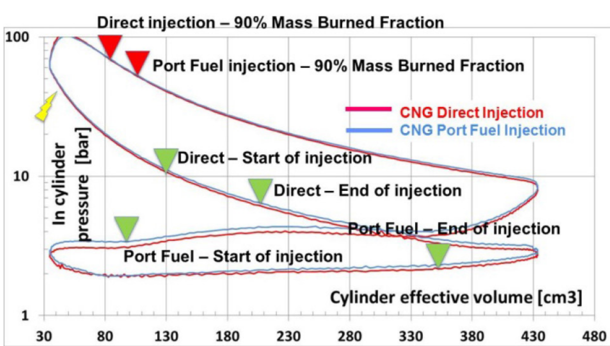

Figure 13. Combustion cycle with injection actuation and combustion duration (5000 rpm - full load)

Lower exhaust gas pressure implies lower pumping work as shown in figure 14. As consequence, at fixed power output, a higher BTE (brake thermal efficiency) is measured with CNG direct injection compared to port fuel injection.

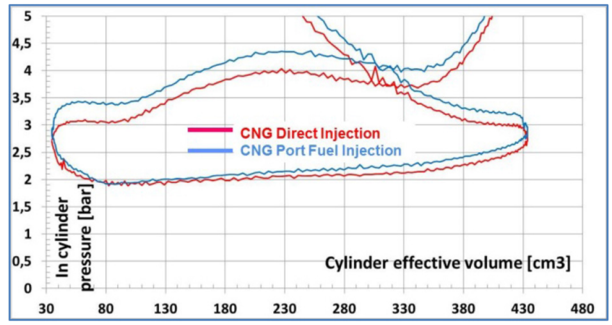

Figure 14. Low pressure side of combustion cycle with CNG direct injection & port fuel injection (5000 rpm - full load)

These results were always achieved complying with:

- stoichiometric combustion
- high combustion stability (COV IMEP<3%)
- absence of knocking
- Miller cycle [20].

Regarding intake valve control running with CNG fuel, early intake valve closure resulted always superior compared to late intake valve closure improving volumetric efficiency thanks to higher expansion ratio versus conventional Otto cycle as shown in figure 15.

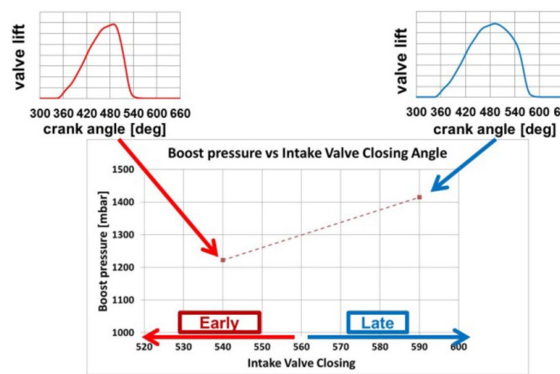

Figure 15. Early intake valve closure mitigates boost pressure at fixed performance

As matter of fact CNG direct injection enhances combustion speed compared to port fuel injection but to explain the physics behind, an additional CFD investigation was carried out computing the turbulence kinetic energy inside combustion chamber (figure 16). Turbulence kinetic energy at spark event is higher with CNG direct injection compared to port fuel injection enhancing combustion speed.

CNG direct injection investigations were completed at partial load also understanding the best injection strategy in terms of end of injection actuation. To explain the behavior of CNG direct injection, a low load engine point is displayed: 2000 rpm - BMEP 4 bar (figures 17 and 18).

Total hydrocarbons emitted by the CNG direct injection engine before 3-way catalyst are a reliable index of air/gas mixing and the figure 17 puts in evidence that the early injection (end of injection @ intake valve open) ensures a very good homogeneity thanks to the long mixing time.

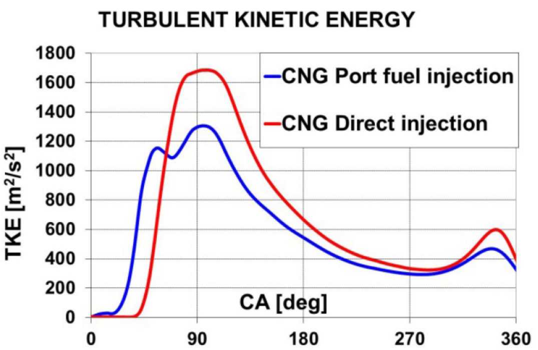

Figure 16. TKE @ 5000rpm full load with CNG direct injection & port fuel injection systems (360 CA means combustion TDC)

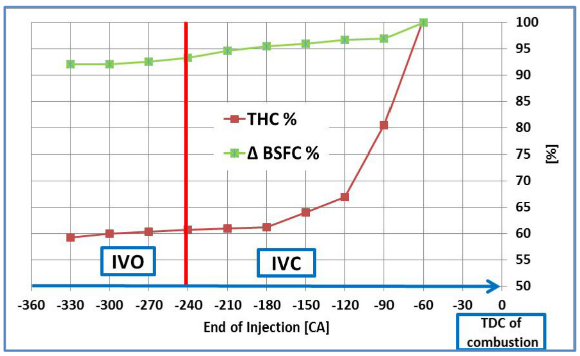

Figure 17. Engine point 2000 rpm - BMEP 4 bar (THC - Total Hydrocarbons & BSFC - Brake Specific Fuel Consumption reduction vs End of Injection - reference 60 CA before TDC of combustion)

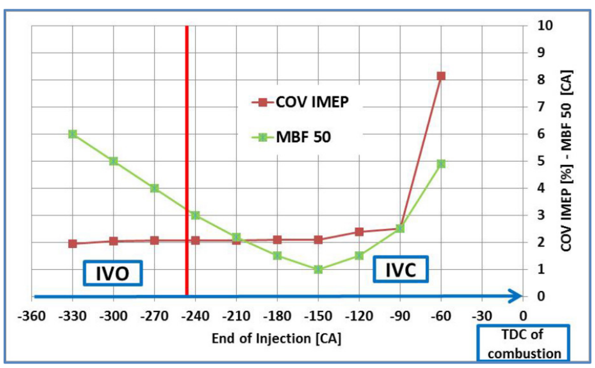

Figure 18. Engine point 2000 rpm - BMEP 4 bar (Combustion duration vs End of Injection - reference 60 CA before TDC of combustion)

On the contrary very late injection (at closed valves, mandatory for scavenging) leads to a less homogeneous mixing; despite of it, the expected increased turbulence can help the combustion process depending on the injection and ignition phasing. Whenever a late injection is recommended for scavenging, a compromise between increase of turbulence and final mixing quality should address the proper injection timing.

The effectiveness of gaseous jet on air motion increasing is not relevant for combustion systems characterized by high air motion level (tumble) itself; this means that the sensitivity of such combustion systems with respect to the injector angular position is not relevant at low loads where weak air motion is expected (due to variable valve actuation) and the quality of air/fuel mixing is dominant on the combustion process. For these cases, beyond the injector position, the early injection strategy is the key factor to enable a good final mixing. Therefore early end of injection shows simultaneously the best air/gas mixing and combustion stability (measured in terms of COV IMEP) with the lowest BSFC / the highest BTE (Brake Thermal Efficiency defined as reverse of Low heat value of the fuel multiplied by BSFC).

Regarding MBF 50 (crank angle at which 50% mass fraction is burned) late end of injection could be similar compared to very early to enhance combustion speed but at partial load air/gas mixing dominates combustion efficiency rather than flame speed.

The results shown at 2000 rpm - BMEP 4bar are extremely similar at other partial load points (from 1500 up to 5000 rpm and from 0 up to 10 bar BMEP) confirming early intake valve closure as the best choice.

Therefore the adoption of late end of injection has been implemented only where the optimal volumetric efficiency can't be achieved with other modalities.

To deploy the BTE benefits due to CNG direct injection, high compression ratio and variable valve actuation (enabling high expansion ratio), additional experimental tests were carried out on the same engine (table 1) and the same test matrix (figure 9) with port fuel injection, low compression ratio (10:1) and mechanical distribution for valve management respectively.

To explain the achieved results of the aforementioned benefit deployment, a couple of engine points are selected among the most relevant and reported in the figures below.

CNG direct injection improves the combustion speed allowing increasing spark advance and BTE consequently (figure 19).

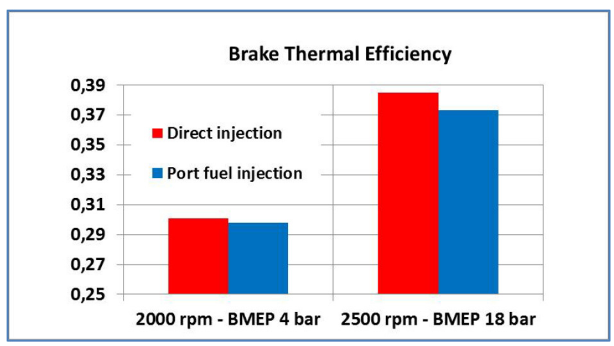

Figure 19. BTE comparison between CNG direct versus port fuel injection at fixed high compression ratio and variable valve actuation

Compression ratio 13:1 versus 10:1 improves engine efficiency of 3-4% depending point by point without any knocking phenomena due high octane number of CNG (figure 20).

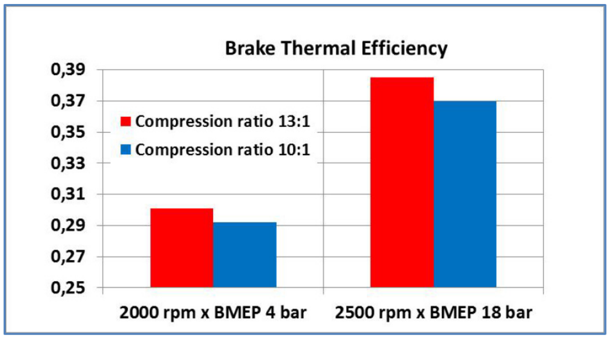

Figure 20. BTE comparisons between high versus low compression ratio at fixed CNG direct injection and variable valve actuation

Variable valve actuation enables a combustion cycle with high expansion ratio in every operating point by means of early intake valve closure and related boosting not feasible with mechanical distribution. The over expanded air through intake valves is cooled into combustion chamber allowing to increase spark advance and BTE consequently.

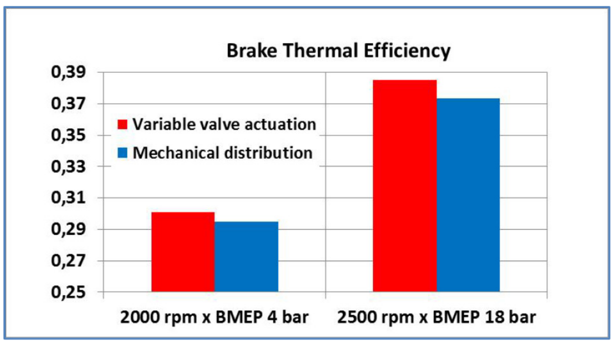

Figure 21. BTE comparisons between variable valve actuation and mechanical distribution at fixed CNG direct injection and high compression ratio

The experimental investigations were completed with pressure sweeps of CNG direct injection to measure the impact on fuel consumption. Nevertheless influence on fuel consumption is very limited; the recommendation is to have a variable pressure management to respect system constraints: sonic flow, injection duration, and injection stability. Even if the lowest pressure value (8 bar abs) is preferred to get the highest vehicle range, at BMEP > 10bar a higher pressure value is requested (up to 16 bar abs) to guarantee the adequate flow rate to execute the entire injection when intake valves are closed.

Conclusions

According to the CFD and experimental analysis carried out, the side direct injection of CNG enables a good air/gas mixing close to spark plug before ignition and influences tumble motion enhancing combustion speed.

At full load CNG direct injection versus port fuel injection fully removes volumetric efficiency losses and at low engine speed the scavenging is enabled by synergic effects with variable valve actuation system. At rated power CNG direct injection enhances turbine efficiency and air/gas mixing, lowering boost as well as compressor speed with further fuel consumption reduction.

At partial load CNG direct injection versus port fuel injection improves combustion speed with similar combustion stability and air gas mixing with positive effect on BTE (brake thermal efficiency).

The recipe to design a high efficient CNG engine is the matching of direct injection with high expansion cycle ratio through early intake valve closure and high compression ratio. High octane number of CNG removes any knocking limitation to implement high compression ratio at any engine speed and load.

The overall benefits of these combined technologies compared to conventional CNG port fuel injection with low compression ratio (10:1 suitable for gasoline operations) are as follows:

- Gasoline-like performance both in terms of low end / rated torque and rated power
- 1-3% BTE improvement due to the implementation of direct injection
- 3-4% BTE improvement due to the implementation of high compression ratio
- 2-3% BTE improvement due to the implementation of high expansion ratio.

The above mentioned recipe to obtain high efficient CNG engines could be easily implemented in modern gasoline direct injection engines if the CNG direct injector was sufficiently robust for automotive standards.

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Definitions/Abbreviations

A/F - Air to Fuel Ratio

BMEP - Brake Mean Effective Pressure

BSFC - Brake Specific Fuel Consumption

BTE - Brake Thermal Efficiency

CA - Crank Angle

CNG - Compressed Natural Gas

COV IMEP - Coefficient of Variation of Indicated Mean Effective Pressure

DI - Direct Injection

EIVC - Early Intake Valve Closure

GDI - Gasoline Direct Injection

IVC - Intake Valve Close

IVO - Intake Valve Open

LIVC - Late Intake Valve Closure

MBF - Mass Burned Fraction

P_{cyl} - Pressure into combustion chamber

P_{CNG} - CNG pressure downstream injector

P_{rail} - CNG pressure upstream injector

PFI - Port Fuel Injection

RPM - Revolutions Per Minute

TDC - Top Dead Center

VVA - Variable Valve Actuation

WOT - Wide Open Throttle

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