INJECTION TIMING EVALUATION OF A COMPRESSED NATURAL GAS DIRECT INJECTION ENGINE BASED ON EXPERIMENTAL DATA AND ONE-DIMENSIONAL SIMULATION

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Abstract. Compressed Natural Gas (CNG) is a widespread hydrocarbon fuel in power generation, commonly injected upstream from the intake valves of an internal combustion engine, reducing volumetric efficiency and consequently power density. Recent developments use Direct Injection (DI) to overcome these losses. Some aspects regarding injector construction, injection pressures and flow rates are essential to the success of CNG - DI. This paper demonstrates the usefulness of a one-dimensional simulation tool such as GT-Power to check injector capabilities under operational conditions. The main parameter analyzed was volumetric efficiency for different injection timings, which is directly proportional to the maximum engine power output for a given speed and air to fuel ratio. Simulation was calibrated using experimental data from a Single Cylinder Research Engine (displacement of 2059 cm³).

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1 INTRODUCTION

In recent years, compressed natural gas (CNG) has become a very competitive fuel for power generation applications, and is now commonly used in spark ignited internal combustion engines, gas turbines, steam power plants and fuel cells.

Mixers and Port Fuel Injectors (PFI) are usually applied as CNG injection methods for engines. The fuel is injected upstream the intake valves, competing with air during intake stroke, reducing the amount of oxygen available to the combustion and consequently the power density.

Recent developments use Direct Injection (DI) with late injection timings (after intake valve closes) in order to eliminate CNG fuel mass influence on the intake process. With this concept Caley and Cathcart (2006) where able to increase air flow up to 10% for low speeds and 4% at 5000 revolutions per minute in a 450 cm³ engine, with injection pressure of 22 bar. This shows a particular operational characteristic of late injection regarding mixture preparation: at high speeds and loads, late direct injection combined with long pulse duration can negatively affect mixture preparation, increasing cyclic variability in combustion and non-burned fuel emissions.

In order to understand how aspects such as different injection timings and pressures affect volumetric efficiency, a computer model of the system was built using GT-POWER one-dimensional cycle simulation tool, able to conduct simulation on a wide variety of internal combustion engine concepts using an object-oriented language with several templates to model heat transfer, friction and combustion.

As this work focuses on volumetric efficiency evaluation, special attention must be given to the intake process. Complementary internal features of the software, such as combustion, engine friction and in-cylinder heat transfer models, have shown low impact over volumetric efficiency during initial research, and the standard parameters suggested by the users' manual were adopted.

2 MATERIALS AND METHODS

An engine model was built and calibrated using experimental data from a Single Cylinder Research Engine (see Figure 1) specially designed and manufactured for research on CNG and Ethanol fuels. It has independent intake and exhaust camshafts, variable compression ratio and a complete intake air conditioning station. In order to reduce air humidity influence on the experiment, relative humidity was controlled to within 0.2%.

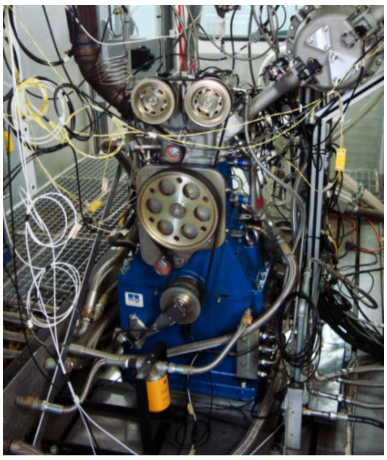

Figure 1 - Single cylinder research engine

The selected speed for this study was 1800 revolutions per minute (RPM), which corresponds to a 60 Hertz synchronous generator (4 poles) directly coupled to the engine.

2.1 Engine model

The engine model is based on components' collected geometry and flow characteristics. Intake and exhaust systems are basically different pipes connecting the environment (*env* and *exh* at Figure 2) to the poppet valves; their discharge coefficients were measured using a specific flow bench. Lift profiles are crank angle based (°CA) and can be observed in Figure 3.

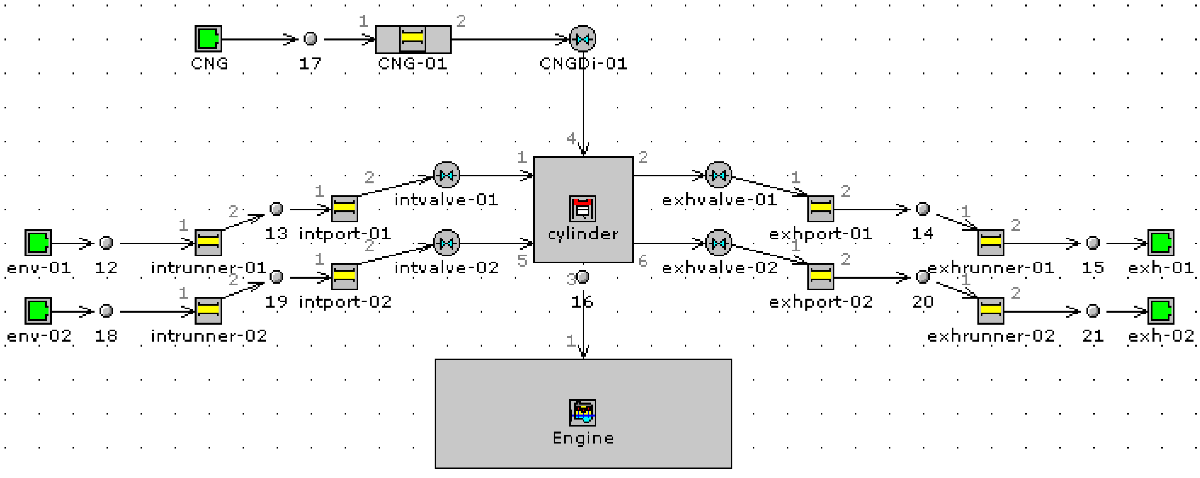

Figure 2 - Engine model using GT-POWER

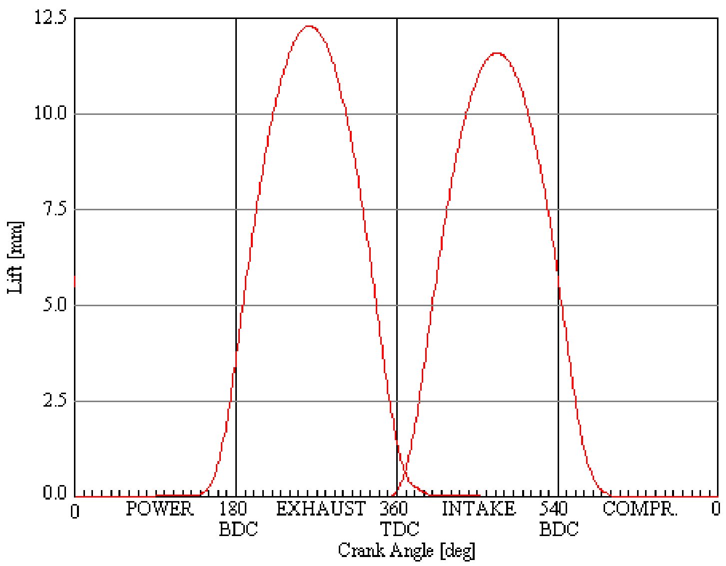

Figure 3 – Valve lift profiles

Intake and exhaust poppet valves, as well as the CNG direct injector, are directly connected to the cylinder template (bore, stroke and compression ratio). The cylinder is then connected to the engine template, comprising crankshaft radius and connecting rod length, completing the engine geometric model.

Bore	128 mm	Intake Valves Open	353 °CA
Stroke	160 mm	Intake Valves Close	601 °CA
Displacement	2059 cm^3	Exhaust Valves Open	134 °CA
Compression Ratio	13 : 1	Exhaust Valves Close	399 °CA

Table 1 - Main engine parameters

The GT-POWER solution method is based on component discretization in sub-volumes connected by boundaries, with the engine cycle divided in many time steps. For each time step a simultaneous solution for conservation of mass, energy and momentum equations is computed at sub-volumes and boundaries.

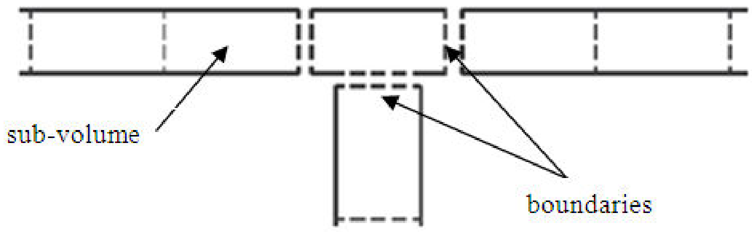

Figure 4 – Component discretization

Time step (Δt) is calculated considering Courant number (σ) criteria in terms of discretized element length (Δx), fluid velocity (u), and sound speed (c) for the critical component (see Eq. (1)). Gamma Technologies (2006) suggested that this software remains stable for Courant numbers up to 0.80.

$$\sigma = \frac{\Delta t}{\Delta x}.(|u| + c) \tag{1}$$

During this stage, initial discretion element lengths are set for each component, and are adjusted by the algorithm during solving process.

2.2 Volumetric efficiency from experimental data

Intake process was adjusted based on Single Cylinder Research Engine data running with direct injection. Air flow data was obtained from fuel mass flow rate (m_{cng}) and the measured lambda factor (λ), as defined in Eq. (2):

$$\mathrm{m_{air}} = \dot{\mathrm{m}}_{\mathrm{cng}}.\lambda.\mathrm{AF_{st}} \tag{2}$$

CNG fuel was characterized as a composition of 5 hydrocarbon species, carbon dioxide and nitrogen, according to their mass fractions, presented in Table 2.

Methane	78,2 %	Pentane	0,8 %
Ethane	10,1 %	Hexane	0,3 %
Propane	4,1 %	Carbon dioxide	3,6 %
Butane	1,9 %	Nitrogen	1,0 %

Table 2 - CNG composition (mass fraction)

For this composition, the complete burn of one mass unit of CNG (only water and carbon dioxide as combustion products) demands 15.58 mass units of air, corresponding to the stoichiometric air / fuel ratio (AF_{st}). Lambda factor is defined in Eq. (3) using actual air / fuel ratio (AF_{ac}).

$$\lambda = \frac{\mathrm{AF_{ac}}}{\mathrm{AF_{st}}} \tag{3}$$

Heywood (1988) defines volumetric efficiency (η_v) as the volume flow rate of air (m_{air}) into the intake system divided by the rate at which volume is displaced by the piston. It is a function of displaced volume (V_d), speed (N) and number of revolutions per cycle (2, in a 4-stroke engine). Air reference density (ρ_a) is taken usually from the environment.

$$\eta_v = \frac{2.m_{air}}{\rho_a\,.V_d.N} \tag{4}$$

The propagation of uncertainty for volumetric efficiency is based on partial derivatives of its function regarding each variable and associated uncertainty.

2.3 Direct injector

A CNG injector for 25 bar nominal fuel pressure was used. The operational principle is based on a poppet valve with opening controlled by a solenoid, brought back to the closed position by a pre-loaded spring. Reference diameter and lift are 8 mm and 0.2 mm respectively.

Opening and closing characteristic time is 1 millisecond (or 10.8 °CA at 1800 RPM). Formally, start and end of injection (SOI and EOI) are defined as the period during which the solenoid is acting. Mechanically, after 1 millisecond of electrical excitation at the solenoid, lift reaches its maximum, remaining there until the electrical pulse ends. These events were modeled as constant slopes at GT-POWER with 10.8 °CA duration. SOI and EOI formal definitions were kept as references for discussion.

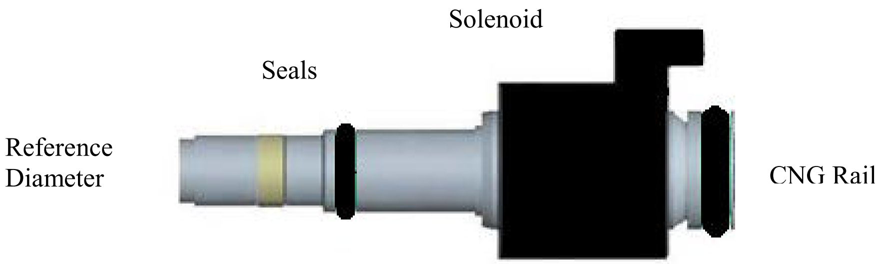

Figure 5 - CNG injector

As the injector operates mainly choked (mach = 1) due to its high pressure ratio, fuel mass flow rate was adjusted via discharge coefficient using experimental data.

3 RESULTS AND DISCUSSIONS

All the simulations achieved convergence criteria (<0.2% in mass) in 10 cycles or less. Computational time was approximately one minute for each case using a Core 2 duo, 2 GHz, 1 GB DDR2 memory work station.

3.1 Experimental correlation

Experiments were conducted at 1800 RPM for 3 different fuel mass flow rates. Intake air pressure was adjusted to reach 1.00, 1.30 and 1.50 of lambda factor with start of injection (SOI) taking place at 413° CA, or 60° CA after intake valve opening. At each point, with fixed fuel flow and intake air pressure, SOI was retarded in 40 °CA. The data displayed at Table 3 corresponds to average values of 100 cycles.

Fuel Flow [Kg/h]	SOI [º CA]	Lambda Factor	Volumetric efficiency	
6.61 ± 0.04	413	1.01 ± 0.01	80.4 ± 1.2 %	Case A
6.57 ± 0.04	453	1.03 ± 0.01	81.9 ± 1.2 %	(+ 1.5%)
7.02 ± 0.05	413	1.30 ± 0.01	110.3 ± 1.7 %	Case B
6.99 ± 0.05	453	1.32 ± 0.01	111.6 ± 1.7 %	(+ 1.3%)
8.18 ± 0.06	413	1.51 ± 0.01	148.8 ± 1.9 %	Case C
8.12 ± 0.06	453	1.54 ± 0.01	150.5 ± 1.9 %	(+ 1.7%)

Table 3 - experimental data from a single cylinder engine.

Injection duration and fuel pressure were kept constant, but fuel mass flow meter system uncertainty strongly affects volumetric efficiency uncertainty. Assuming that injected fuel mass is constant, the effect on lambda ratio shows an increase in volumetric efficiency, although it is hard to quantify it from this data.

Performing a calibration of the model using SOI 413° CA as reference (cases A, B and C), Table 4 was constructed based on GT-POWER results. The same tendency on volumetric efficiency can be observed on simulation, validating the model.

Fuel Flow [Kg/h]	SOI [º CA]	Lambda Factor	Volumetric efficiency	
6.54	413	1.02	80,4%	Case A
6.54	453	1.03	81,7%	(+1.3%)
7.01	413	1.31	111,0%	Case B
7.01	453	1.32	112,0%	(+1.0%)
8.22	413	1.50	149,2%	Case C
8.22	453	1.52	150,8%	(+1.6%)

Table 4 - Model validation shows same tendency on volumetric efficiency.

Based on this model and boundaries conditions of tests with SOI 413 (case A), volumetric efficiency for port fuel injection (PFI) and no fuel injection conditions were studied. No fuel was simulated by attributing zero to the injector lift. This corresponds to the ideal intake process, and is useful to determine how far from it the real system operates. Setting environment as an air-CNG mixture, PFI simulation was easily carried.

Fuel Flow [Kg/h]	Injection	Lambda Factor	Volumetric efficiency	
0.00	No Fuel	-	85.0%	Case A (+4.6%)
0.00	No Fuel	-	115.3%	Case B (+4.3%)
0.00	No Fuel	-	153.6%	Case C (+4.5%)
6.54	PFI	0.98	112.0%	Case A (-2.8%)
7.01	PFI	1.27	149.2%	Case B (-3.3%)
8.22	PFI	1.46	150.8%	Case C (-4.4%)

Table 5 - Simulated PFI and no fuel injection conditions.

These results show that the adoption of CNG direct injection increases volumetric efficiency absolute values by at least 3%, compared to PFI, although no fuel injection indicates full potential of 7%. Additional retard on SOI increased volumetric efficiency in 1%.

3.2 Injection timing evaluation

After calibration and model validation, experimental conditions of case A were selected as reference for an injection timing evaluation. Fuel mass flow rate, intake and exhaust pressures were kept constant. Start of injection was varied within a range limited by intake valve opening event and in-cylinder pressure near the top dead center, in order to avoid reverse flow through the injector.

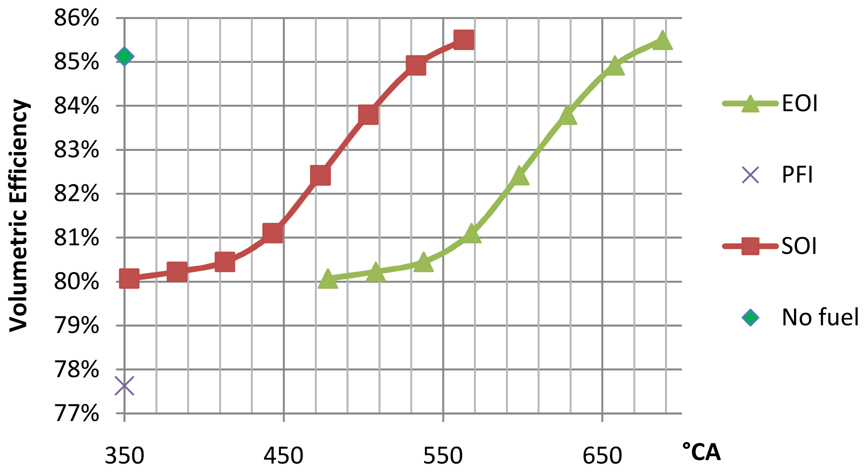

Figure 6 - Injection timing effect on volumetric efficiency

Figure 6 confirmed the hypothesis of fuel injection influence on the intake process. Volumetric efficiency to direct injection reaches no fuel condition levels only to very late injections (SOI near intake valves closing event).

In-cylinder pressure curves are shown in Figure 7 for early and late direct injection. This slight difference in pressure could explain air flow mass reduction, since intake pressure, lift and discharge coefficients of intake valves remain constant.

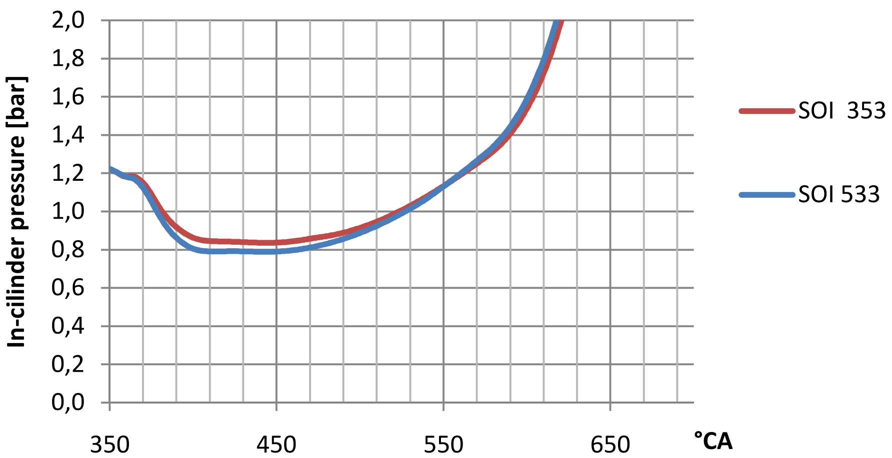

Figure 7 - In-cylinder pressure for different start of injection

3.3 Injection pressure sensibility

Using the same principle of injection timing evaluation, case A is used for an injection pressure sensitivity analysis. Fuel pressure is set to 20, 25 and 30 bar adjusting injection durations to keep fuel mass constant, for four different SOI limited by the worst end-of-injection scenario regarding in-cylinder pressure.

As expected from the shocked flow hypothesis on the injector, injection duration exhibited a linear dependence on injection pressure: 156.0, 126.8 and 107.6 °CA for 20, 25 and 30 bar respectively. Gains in volumetric efficiency (Figure 7) are related to PFI condition.

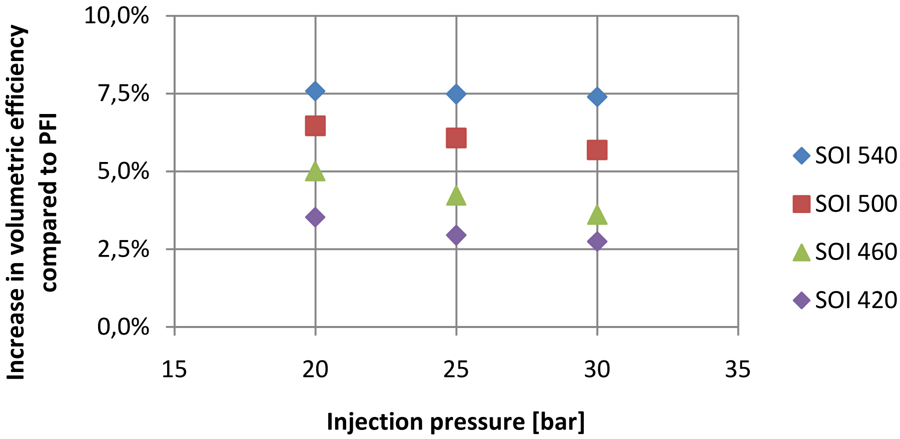

Figure 8 - Volumetric efficiency for different injection pressures and timings

In the studied cases volumetric efficiency is the same for late injection. The behavior for early injection could be explained by the fast fuel injection (due to higher pressure) affecting in-cylinder pressure and consequently reducing fuel mass flow rate, similarly to what is shown in Figure 7. To compensate for this effect, higher injection pressures would require later SOI. A simple approach would be to keep constant the same end of injection, as shown in Figure 7.

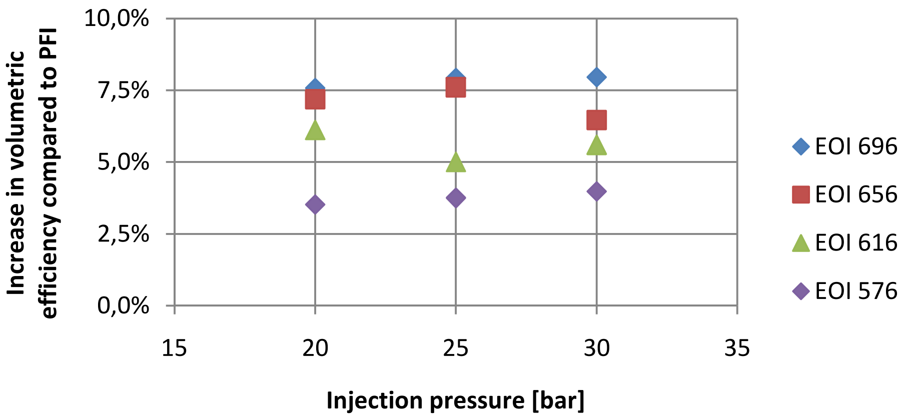

Figure 9 - Volumetric efficiency for different injection pressures keeping EOI constant

From these results it seems possible to keep volumetric efficiency for higher injection pressures and early injection by adjusting new SOI and EOI in one intermediate region related to previous reference injection timing.

4 CONCLUSIONS

The construction of a GT-POWER model and its validation via experimental data allowed the characterization of a CNG direct injector regarding injection timing, pressure and their impact on volumetric efficiency.

From the comparison of experimental results for 1800 RPM and three different lambda factors, the adoption of CNG direct injection shows increases on volumetric efficiency absolute values of at least 3%, compared to PFI.

Taking 1800 RPM and lambda factor 1 as references for fuel mass flow rate, intake and exhaust pressures, PFI configuration had 77.6% of volumetric efficiency. Full potential of late injection (8% of absolute increase compared to PFI) was reached for SOI near the intake valve closing event, confirming the hypothesis of fuel influence on the intake process.

A linear dependence was found between injection flow rate and injection pressure. It affects volumetric efficiency behavior, requiring adjustments on SOI.

5 ACKNOWLEDGEMENTS

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