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# Comparative study between early and late injection in a natural-gas fuelled spark-ignited direct-injection engine

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**Abstract**

Natural gas is a cleaner burning alternative fuel that has the potential to widely replace conventional fuels. The use of Compressed Natural-Gas (CNG) in spark-ignited (SI) engines can reduce $CO_2$ emissions by up to 20% compared with gasoline operation. Currently, all spark-ignited CNG engines for passenger vehicles are port-fuel injected (PFI). They suffer loss of peak torque and power due to a reduction in volumetric efficiency. Direct-Injection can overcome this drawback by injecting the fuel after intake valve closure, leading to significant improvements in torque output. In this experimental study, we present the effects of injection timing, before and after the inlet valve closure on combustion duration and engine thermal efficiency at low load and WOT (Wide Open Throttle) conditions. At low-loads, late-injection increases pumping losses compared to early-injection at a given loading condition but combustion is faster due to higher turbulence at the time of ignition. As a result, the thermal efficiencies are similar at these injection timings.


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*Keywords:* CNG; direct-injection; early-injection; late-injection; pumping losses.

## 1. Introduction

The automotive industry faces a greater challenge today to reduce harmful pollutants and $CO_2$ emissions. This has promoted the industry to revisit natural-gas as fuel for spark-ignited internal combustion engines for its potential to improve engine efficiency, performance and emissions. In [1], the authors have carried out an extensive review of natural-gas as a transportation fuel which is considered as the most promising alternative fuel. Although, port-injected

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CNG technology is tried and tested, it has not become as popular as conventional fuelled vehicles particularly in passenger vehicle market. One of the reasons besides lack of infrastructure and refueling stations is the lower torque and power output compared to gasoline in bivalent vehicles. This is due to reduced volumetric efficiency as the gaseous fuel displaces incoming fresh air resulting in reduced peak torque and power. This inherent drawback exists in dedicated CNG engines as well. Direct-injection can overcome this loss of torque by injecting the fuel after intake valve closure. This has been well reported in the literature by many researchers [2]. Recently [3] reported a significant improvement in torque at low speed and full-load condition using direct-injection with an optimized injector for natural-gas in conjunction with turbocharging. At part-loads, direct-injection has higher pumping loss compared to port-fuel injection. Recently [4] have also assessed the performance of CNG direct-injection compared to gasoline and CNG port injection using a prototype CNG direct-injector and have got similar trends. This study highlights the effects of injecting the fuel before and after the intake valve closure period on combustion performance at stoichiometric air-fuel ratio condition.

## 2. Experimental Method

The test regime consisted of operating the engine at three speed points (1000, 1500 and 2000 RPM) and four load points (2, 4, 6 bar IMEP and WOT condition). A sweep of start of injection (SOI) is carried out for both early and late injection periods for all engine operating points and the optimum SOI in terms of lowest coefficient of variation (CoV) in IMEP and fuel flow rate is considered. The SOI for early-injection is during the valve open period and for late-injection it is during and/or after the intake valve closure. The ignition dwell time is kept constant at 4 ms and the ignition timing is optimized such that 50% of mass fraction burned location is at 8-10º aTDC (CA50)

The Engine Specifications are as per Table 1 below.

Table 1. AVL single cylinder naturally aspirated research engine specifications.

| Engine Parameter | Dimension |
|---|---|
| Bore | 82mm |
| Stroke | 90mm |
| Capacity | 475.5 cc |
| Conrod Length | 147.5 mm |
| Compression Ratio | 10.55:1 |
| Twin Overhead Valve configuration, with 4 valves, 2 inlets, 2 exhaust. | |
| Inlet Valves Diameter | 31mm |
| Exhaust Valves Diameter | 27mm |
| Valve Overlap | 18º |
| Piston: Shallow Bowl (2.7 mm deep), Diameter of the bowl: top of bowl 73 mm, bottom of bowl 63 mm). | |

A Bosch GDI multi-hole injector controlled by a Bosch HDEV1.1/HDEV1.2 controller which responds to a TTL pulse generated from the AVL control system is used to inject the required mass of fuel into the engine to meet air/fuel ratio requirements. The fuel pressure is kept constant at 100 bar. Natural-gas is issued to the injector from commercial CNG cylinders through two stage pressure reductions (200-150 bar and 150-100 bar) via two pressure regulators. The flow rate of the fuel is measured by a coriolis flow meter (Siemens Sitrans FC300) connected to mass flow readout (Siemens Sitrans). The temperature of engine oil and coolant are maintained at 90º C. The methane content in the fuel is about 90% and the energy content is 44.68 MJ/kg. In-cylinder pressure measurement is carried out for 100 consecutive cycles and the average values are presented.