21st Australasian Fluid Mechanics Conference
Adelaide, Australia
10-13 December 2018

Study of Natural Gas Injection Timings on a Downsized and Boosted, Multi-Cylinder Direct Injection (DI) Engine

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Abstract

This study presents experiments conducted on a 4-cylinder, downsized and boosted, direct injection (DI) engine fuelled with compressed natural gas (CNG). The impact of injection timing on engine performance was investigated by varying the start of injection (SOI) from an advanced timing during the induction stroke to a retarded timing close to intake valve closure. Injection timings that are too advanced or too retarded result in lower brake thermal efficiency (BTE), whereas intermediate SOI timings increase BTE. An analysis of mixing time, intake air flow, and combustion process are performed to understand the impact of injection timing on the DI CNG engine performance.

Introduction

Improvement in internal combustion engine (ICE) efficiency is imperative given the cost uncertainty and diminishing supplies of petroleum-based fuels, as well as the demands of increasingly strict emissions regulations. Compressed natural gas (CNG) has emerged as a promising alternative to conventional refinery stream fuels due to its favorable properties including low energy specific CO_2 emissions, high antiknock resistance and an extended lean flammability limit.

Current natural gas fuelled automotive engines using port fuel injection (PFI) technology have limitations on peak torque and power compared to gasoline fuelled equivalents as a result of intake air displacement by the natural gas [1, 2]. This has provided much of the motivation to study natural gas DI engines, in an effort to overcome the limitations of NG PFI. Ferrera et al. [3] found 1-3% BTE improvement over CNG PFI operation due to the implementation of direct injection. Several authors [4, 5, 6] studied different aspects of CNG DI engine behavior under various operating parameter such as rail pressure, fuel injection, spark timing etc. Husted et al. [7] showed that up to two-thirds of the lost torque in NG PFI operation compared to GDI operation can be recovered with DI CNG. Sevik et al. [8] studied the effect of injection timings on the performance of a single cylinder engine equipped with NG DI, NG PFI and E10 PFI system and showed similar efficiencies at part load operation for both E10 and CNG.

Although these studies have provided a preliminary characterisation of DI CNG engine performance, there is still uncertainty as to how DI CNG will operate in a modern, DISI production engine and how best to optimise the injection strategy for such an engine. Therefore, this study aims to investigate the performance of an advanced DISI production engine using injectors optimised for CNG delivery at various SOI timings.

Experimental Set-up and Procedure

A Ford 2.0L EcoBoost (4-cylinder, downsized and boosted, DI) engine was used for this experimental study. The engine configuration is given in table 1. The specifications of mains natural gas used for this study are given in table 2. An outward opening,

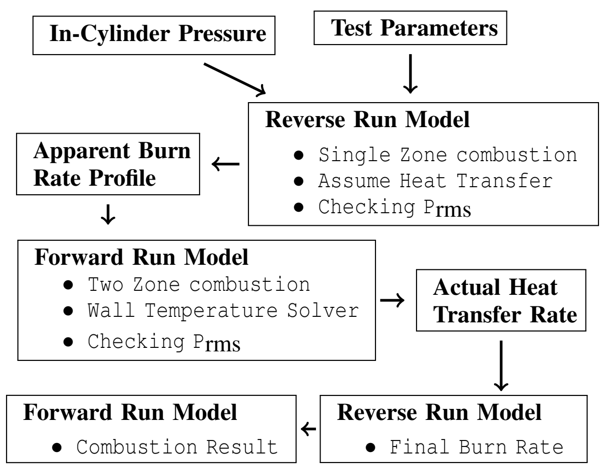
Table 1: Engine Specification

Bore	87.5 mm
Stroke	83.1 mm
Displacement	2 L
Compression Ratio	9.3
Injection Pressure	16 bar
Injector Orientation	Side Mounted
Ignition Source	Spark Plug

Table 2: Natural gas specification

Composition by Volume [9]	
Methane (CH_4)	92.25 %
Ethane (C_2H_6)	4.42 %
Propane (C_3H_8)	0.69 %
Nitrogen (N_2)	0.84%
Carbon-Di-Oxide (CO_2)	1.8%
Property	
LHV	47.3 MJ/kg
AFR Stoich	16.0

prototype valve type injector from Continental was used to supply CNG at a constant 16 bar pressure to the cylinder. A Bosch hot-film, air-mass meter and a Coriolis flow-meter were used to measure air and the CNG flow rate, respectively. A Bosch LSU 4.9 lambda sensor was installed on exhaust pipe to measure and monitor the air-fuel ratio on-line. The engine was run with an open, developmental MoTec M142 ECU. Four Kistler piezoelectric pressure sensors and a crank angle encoder with 0.1 CAD resolution were installed to record the in-cylinder pressure history. The ensemble average of 300 successive pressure traces was used to conduct heat release analysis in GT-Power based on the following non-predictive combustion methodology. The experiment was conducted at an engine speed of 1500



RPM and 6 bar BMEP. Several CNG SOI timings ranging from 120 $BTDC_F$ to 320 $BTDC_F$ were tested at $\lambda = 1$. Generally, the most retarded SOI timing is limited by the choked fuel flow condition and available fuel-air mixing time between the end of injection and spark timing, whereas the most advanced SOI is limited by excessive CNG flow back into the intake manifold. Maximum brake torque (MBT) timing was maintained in all test conditions by adjusting spark timing to target 50% MFB location $\sim$ 8-10 CAD $ATDC_F$.

In present experimental study, SOI timings are categorized into three zones as shown in Figure 1 and defined as advanced SOI, i.e. fuel injection proceeding towards intake valve opening (IVO), retarded SOI, i.e. injection towards intake valve closing (IVC) and intermediate SOI as injection between these two.

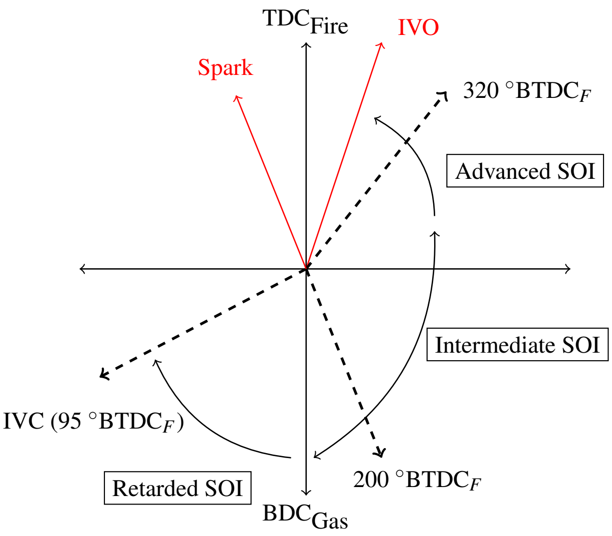


Figure 1: Fuel Injection Timings on Valve Timing Diagram

Results and Discussion

Figure 2 shows brake thermal efficiency (BTE) as a function of SOI timing. BTE is affected by SOI and decreases for both injection retarding towards intake valve closing (IVC) (120 deg $BTDC_F$), as well as fuel injection at the early part of the intake stroke (320 deg $BTDC_F$). Consequently, there is an optimal BTE at an intermediate SOI. SOI timings spanning from 200 to

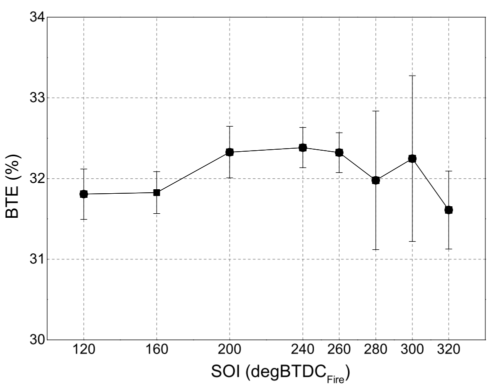


Figure 2: Brake Thermal Efficiency

300 CAD $BTDC_F$ demonstrate higher efficiency area considering all measurement uncertainty, however, selection of the most favourable BTE zone must also account for combustion stability and engine exhaust emissions.

Figure 3 presents the coefficient of variance of the indicated mean effective pressure (IMEP) to show combustion variability at each tested condition. COV of IMEP less than 3% generally represents acceptably stable engine operation. Both overly ad-

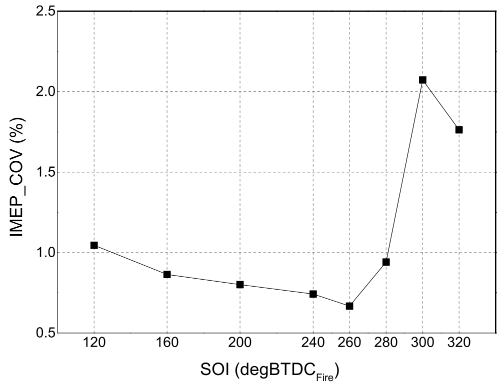


Figure 3: COV of IMEP

vanced (320 deg $BTDC_F$) and retarded (120 deg $BTDC_F$) SOI produce comparatively high COV and beyond these SOI points, extremely unstable engine operation is observed. Among the tested injection timings, SOI spanning from 240 to 260 CAD $BTDC_F$ produces high BTE with low COV and therefore, is considered as the most ideal SOI zone for this particular engine speed and load.

Figure 4 presents intake manifold pressure (MAP), valve lift profile and available air-fuel mixing time before spark as a function of SOI to provide an explanation of the BTE behavior with varying injection timing. As CNG displaces intake air, the engine is more dethrottled at advanced SOI timings compared to retarded SOI to maintain the same load. Therefore, there is a higher absolute manifold pressure at advanced SOI. The inertia associated with gaseous CNG injection is lower than liquid fuels and it is conjectured that assistance from the intake air flow is needed for better mixing of the fuel-air charge. At highly ad-

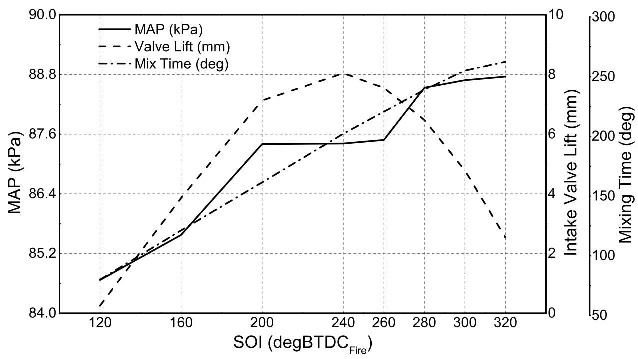


Figure 4: MAP, Valve Lift and Mix Time

vanced SOI, less air flow associated with a CA position of low valve lift negates the benefits of more available mixing timing, whereas a highly retarded SOI suffers from less mixing time and high pumping loss associated with low manifold pressure. The optimal timing zone (SOI 240 to 260 CAD $BTDC_F$) benefits from both relatively long mixing time and favourable location of high air flow corresponding to the higher intake valve lift of the conditions tested.

Figure 5 shows combustion efficiency trend with experimental uncertainty as a function of SOI and is calculated based on the wet exhaust emissions of CO, unburned HC (C1 basis) and H_2 as follows:

$$\eta_c(\%) = 1 - \frac{X_{\mathrm{CO}} \times LHV_{\mathrm{CO}} + X_{\mathrm{UHC}} \times LHV_{\mathrm{fuel}} + X_{\mathrm{H_2}} \times LHV_{\mathrm{H_2}}}{\frac{\dot{m}_{\mathrm{fuel}}}{\dot{m}_{\mathrm{fuel}} + \dot{m}_{\mathrm{air}}} \times LHV_{\mathrm{fuel}}} \tag{1}$$

CO, CO_2 and UHC mole fraction are directly measured in dry form using Horiba Analyzer, whereas H_2 fraction is calculated using dry CO and CO_2 mole fraction. All dry amount is then converted to wet form using empirical equations [10].

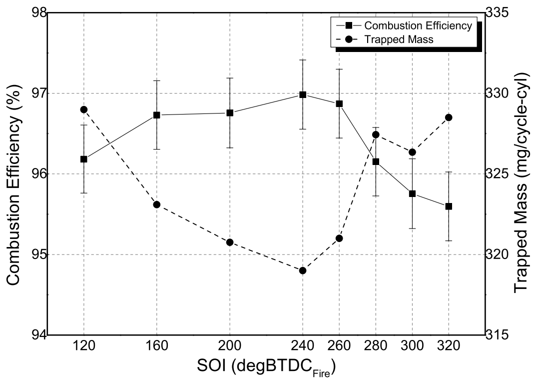


Figure 5: Combustion Efficiency and Trapped Mass

The highest combustion efficiency zone appears at the SOI span of 240 to 260 CAD BTDC$_F$, and it decreases at highly advanced and highly retarded SOI timings, confirming the thermal efficiency trends shown in Figure 2. Trapped mass per cycle-cylinder based on measured air and CNG flow rate supports this plotted combustion behavior trend.

Figure 6 shows brake specific carbon monoxide (CO) and oxygen (O_2) emissions as a function of SOI. When attempting stoichiometric engine operation, exhaust containing CO and O_2 provides an indication of poor charge mixing and incomplete combustion. The trend of brake specific CO and O_2 over the SOI conditions also agrees with the combustion efficiency results and supports the BTE trend.

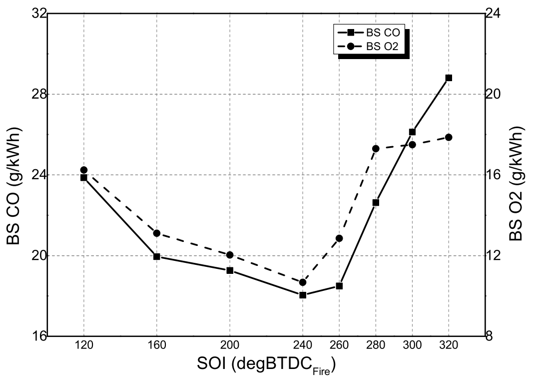


Figure 6: Brake Specific CO and O2

To provide a more detailed explanation for the observed brake trends, heat release analysis has been performed in GT Power and 0% to 90% MFB burn durations are shown in Figure 7. This analysis is based on the non-predictive combustion methodology using measured in-cylinder pressure from the experiments. With overly advanced SOI timings, increasing burn duration trend is observed which results poor combustion with lower BTE. Comparatively shorter burn duration at intermediate SOI timing indicates faster combustion and confirms the previous experimental observations regarding the high BTE zone. However, there is not significant increase of burn duration with retarded fuel injection timings to corroborate low BTE results. In figure 8, high compression pressure prior to ignition at retarded SOI timings is likely the reason for these lower burn duration. This is further supported by high peak cylinder pressure at these SOI timings. Therefore, burn durations are not sufficient enough to completely characterize the engine performance trends.

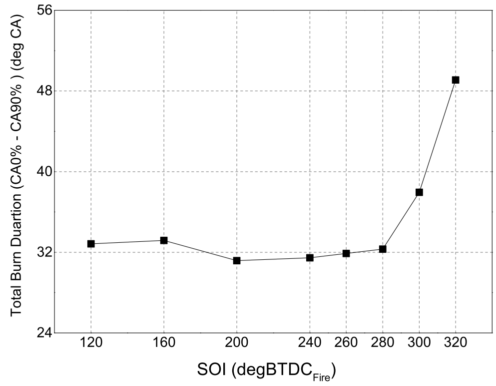


Figure 7: Burn Duration

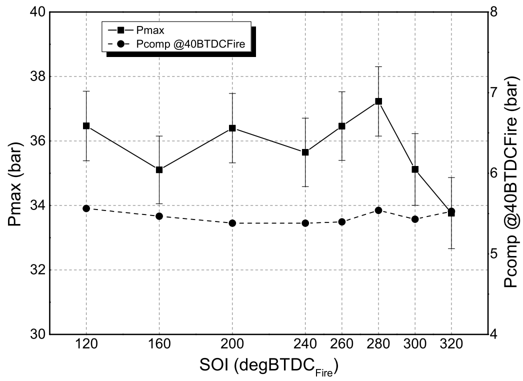


Figure 8: $P_{compression}$ @ 40BTDC$_{Fire}$ and P_{max}

A further analysis based on input fuel energy and work done at each of the four individual stroke in the engine cycle is performed and presented in Figure 9. The percentage of energy for each stroke is calculated as follows

$$\text{Pumping Energy}(\%) = \frac{W_g}{E_f} = \frac{\int_{EVO}^{IVC} pdV}{m_f \times LHV} \tag{2}$$

$$\text{Compression Energy}(\%) = \frac{W_c}{E_f} = \frac{\int_{IVC}^{Spark} pdV}{m_f \times LHV} \tag{3}$$

$$\text{Power Stroke Energy}(\%) = \frac{W_p}{E_f} = \frac{\int_{Spark}^{EVO} pdV}{m_f \times LHV} \tag{4}$$

Based on the cycle analysis, with retarded SOI timing, energy generated in the power stroke is relatively high, which concurs with the high peak pressure shown in Figure 8. However,

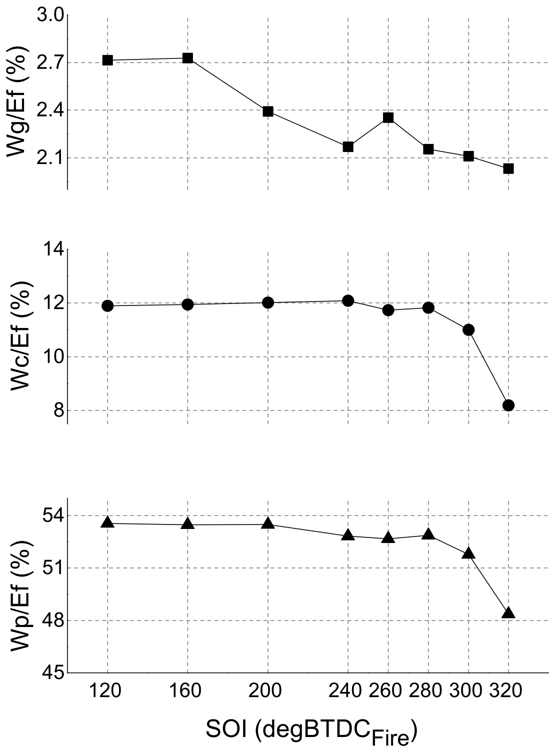


Figure 9: Cycle Energy Analysis

more pumping and compression energy are required with retarded SOI timings due to a lower MAP from more throttling (Fig 4) and high compression stroke pressure associated with fuel injection near BDC_{Gas} (Fig 8). This results in less net work over the cycle and therefore lower overall thermal efficiency at retarded SOI. On other hand, with advanced SOI, low power stroke energy eliminates benefits of lower pumping and compression energy associated with more dethrottling and less compression pressure, resulting lower BTE.

Conclusions

Steady state tests were performed on a CNG fuelled, DI engine at part load for various fuel injection timings, and their impact on engine performance was monitored. At 1500 RPM and 6 bar BMEP, the SOI timings spanning from 240 to 260 CAD $BTDC_F$ produce the most favourable injection timing zone with the highest BTE. This was attributed to a relatively high available mixing time and a CA location coinciding with a high intake valve lift. With advanced SOI timings, a decrease in thermal efficiency was attributed to low intake valve lifts and the possibility of CNG back flow into the intake manifold. The availability of less mixing time with retarded SOI timing appeared to produce poor mixture quality and corresponding low thermal efficiency. The combustion efficiency trend across the range of SOI timings also supports the thermal efficiency results. Combustion analysis revealed shorter burn durations across the intermediate injection timings and confirms the favourability of this injection timings zone. A decreasing trend of combustion duration with retarded injection timings did not directly align with BTE trends. Further cycle analysis showed high pumping energy requirements negated the benefits of shorter burn duration with late SOI, and therefore produced low thermal efficiency.

Acknowledgements

This research was supported by the Ford Motor Company, the Advanced Centre for Automotive Research and Testing (ACART, www.acart.com.au) and the Australian Research Council. We also would like to thank Continental for providing the prototype DI CNG injector hardware.

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Abbreviation

SIDI Spark Ignition Direct Injection
CNG Compressed Natural Gas
$BTDC_F$ Before Top Dead Center Firing
SOI Start of Injection
BDC_{Gas} Bottom Dead Center Gas Exchange

Nomenclature

LHV Lower Heating Value, MJ/kg
BTE Brake Thermal Efficiency, %
BMEP Brake Mean Effective Pressure, bar
MFB Mass Fraction Burned, %
IVO Intake Valve Opening, deg
IVC Intake Valve Closing, deg
COV Coefficient of Variation, %
MAP Manifold Air Pressure, kPa