

Effects of Injection Timing on CAI Operation in a 2/4-Stroke Switchable GDI Engine

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ABSTRACT

A single cylinder direct injection gasoline engine has been developed and commissioned on a transient engine test bed in order to study different engine cycles and combustion modes with identical hardware and operating conditions. The engine can be operated in either 4-stroke cycle or 2-stroke cycle by means of an electro-hydraulic camless system. In addition, both spark ignition and controlled autoignition (CAI) combustion can be achieved. In this paper, effects of the injection timing on different CAI combustion modes are investigated, including the residual gas trapping and exhaust gas rebreathing CAI operations in 4-stroke mode, and also 2-stroke CAI operation, with a stoichiometric air fuel ratio and homogeneous charge used throughout. The performance and emission data are presented and analysed as a function of the injection timing. Results show that the charge cooling effect on the intake flow rate is dependent upon the in-cylinder temperature at the time of injection. The piston wetting by the direct fuel injection should be minimized in order to reduce the high HC emissions and further improve the fuel consumption. Fuel injection timing was also found to affect the combustion phasing through the effect of charge cooling and piston wetting.

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INTRODUCTION

Gasoline Direct Injection (GDI) engine technology has been implemented on many modern production gasoline engines because of its potential benefits to engine efficiency and performance. The introduction of this technology to the gasoline engine is no less important than the replacement of the carburettor by port fuel injection. In the history of developing modern gasoline direct injection engines, GDI was firstly adopted by Japanese automotive manufacturers in the mid-1990s to reduce the pumping loss at part load via stratified charge spark ignition combustion at wide open throttle [1, 2]. Reduction in pumping loss and the overall lean mixture brought the stratified GDI engine better fuel economy. The first generation of the stratified GDI engine was mainly based on guiding the fuel by the wall on the piston crown, which is commonly referred to as the wall-guided combustion system. In this combustion system the injection is linked to the piston position, so the injection timing cannot be largely adjusted to suit different operation conditions. This constrains the stratified combustion to a small speed-load operating range. Such relatively limited range of stratified combustion and the additional cost of the complex and expensive exhaust aftertreatment for the lean-

burn operation enforced a large number of automotive manufacturers to employ a homogeneous charge strategy with the stoichiometric operation [3]. With such stoichiometric operation, the conventional exhaust aftertreatment, i.e. the three-way catalyst can be retained on GDI engines. Recently the second generation of stratified GDI engine has been designed and introduced to market using the spray-guided combustion system. Owing to the recent development in the fuel injector technology a relatively large operating range of stratified charge combustion can be achieved with such a system [4].

An alternative combustion system which can be employed on the GDI engine to reduce the NO_x emission while still attaining the better fuel economy of the GDI engine is Controlled Auto-Ignition (CAI), often known as Homogeneous Charge Compression Ignition (HCCI)[5]. This combustion mode can be realised with a homogeneous mixture in the cylinder and involves auto-ignition combustion at multi-points around TDC. Although CAI can be achieved in PFI gasoline engines, GDI brings the additional means of controlling mixture formation and the CAI combustion process through flexible in-cylinder injection timing, which can alter the process of fuel atomization, vaporization, and fuel reforming. The injection timing can be grouped into 3

categories: (i) early injection before the intake valve opens, (ii) mid injection during the intake process, and (iii) late injection during the compression stroke [6]. The first 2 categories are often referred as homogeneous GDI strategies as the fuel normally has sufficient time to evaporate and mix with the fresh air forming the homogeneous mixture before ignition. Previous research has found that even if under homogeneous conditions, the injection timing has significant effects on the CAI combustion process [5].

In the meantime, the development and application of VVA technology has enabled new engine cycles and combustion processes to be investigated and evaluated for improved fuel efficiency and lower exhaust emissions. Lotus Engineering demonstrated the potential of CAI through negative valve overlap and mode switching between SI and CAI combustion using their fully flexible AVT camless system [7]. AVL demonstrated that CAI/HCCI combustion could also be realised by exhaust gas rebreathing using a set of electro-hydraulic valves to reopen the exhaust valve during the intake process [8]. FEV presented and discussed the fuel consumption and emissions of different exhaust gas recirculation methods achieved by an electromechanical valvetrain [9]. As a member of a consortium, Brunel University has been working with Ricardo UK in developing the 2/4 stroke switchable engine technologies through engine downsizing over the last few years [10], from which the current research on 2-stroke CAI in a poppet valve engine and other advanced combustion technologies has been initiated and performed.

In this paper, the 2/4 stroke switchable single cylinder direct injection gasoline engine and its instrumentation will be presented. By altering the valve timings and durations, CAI combustion was realised in both 4-stroke and 2-stroke modes. In the case of 4-stroke operation, CAI combustion was achieved by means of negative valve overlap and the exhaust gas rebreathing method. The 2-stroke CAI combustion was accomplished by reduced overlap between the exhaust and intake valve openings. Effects of the injection timing were investigated and analysed for the three CAI combustion modes in terms of combustion, performance and emissions.

EXPERIMENTAL SETUP

The engine used in this work is a single cylinder research engine, [Figure 1](#), of which the specifications are shown in [Table 1](#). An electro hydraulic valve train system is mounted on the cylinder head to enable independent control of valve timings and lifts. The fuel is injected via a Denso GDI injector mounted under the intake port at an injection pressure of 100bar. An instantaneous fuel flow meter is installed between the high pressure fuel pump and injector for the measurement of fuel flow rate. An AVL supercharger system is connected to the engine's intake system to supply the compressed air at a pre-set boost pressure and temperature through closed loop control of heaters and heat

exchangers. A laminar air flow meter is installed in the engine's intake system to measure the intake mass flow rate. Both the intake and exhaust pressures were measured by two piezo resistive pressure transducers. The exhaust emissions were analysed by a Horiba 7170DEGR gas analyser which samples the exhaust gases from the exhaust manifold. The instantaneous in-cylinder pressure was measured by a piezo-electric pressure transducer from which the heat release and combustion characteristics could be calculated and displaced on-line using an in-house Labview data acquisition and combustion analysis programme. The engine is mounted on a dynamic engine testbed with fully automated coolant and oil conditioning circuit and driven by an AC motor so that both motored and fired operation could be performed.

Table 1. Engine specifications

Bore × Stroke	81.6mm×66.94mm
Swept volume	0.35L
Compression ratio	11.78:1
Combustion chamber	Pent roof / 4 valves
Valve train	Electro-hydraulic actuation
Fuel injection	Direct injection
Fuel	Standard gasoline (RON 95)
Injection Pressure	100bar
air/fuel ratio	Stoichiometric
Intake temperature	25°C

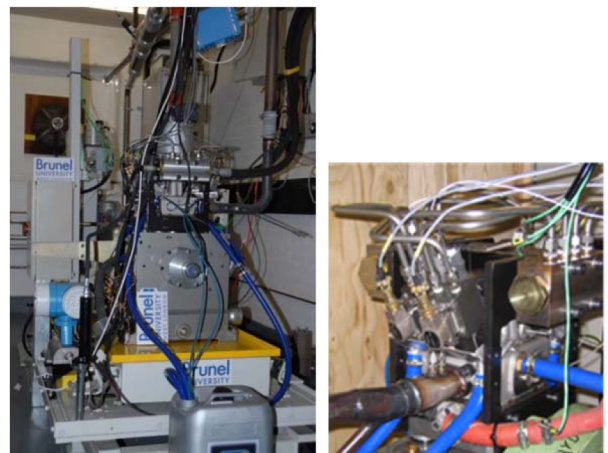


Figure 1. 2/4 switchable DI gasoline engine and camless actuation unit

RESULTS AND DISCUSSION

CAI COMBUSTION OPERATION MODES

The CAI combustion operation was realised by means of three different operating strategies, as shown in [Figure 2](#). They are 4-stroke negative valve overlap (NVO) CAI operation, 4-stroke exhaust rebreathe CAI operation and 2-stroke CAI operation.

Case 1: 4-Stroke NVO CAI Operation

One of the means to achieving CAI combustion is to make use of the heat from recirculating the burnt gases from previous engine cycle. In the 4-stroke NVO CAI operation mode, the burnt gases are trapped in the cylinder by earlier closing exhaust valves. To avoid the backflow of the burnt gases entering the intake port, the intake valve opening time is retarded so that it is symmetric to the exhaust valve closing time on the exhaust TDC. For homogeneous mixture operation, the injection timing can be altered from exhaust valve closure to intake valve closure, as shown in Figure 3.

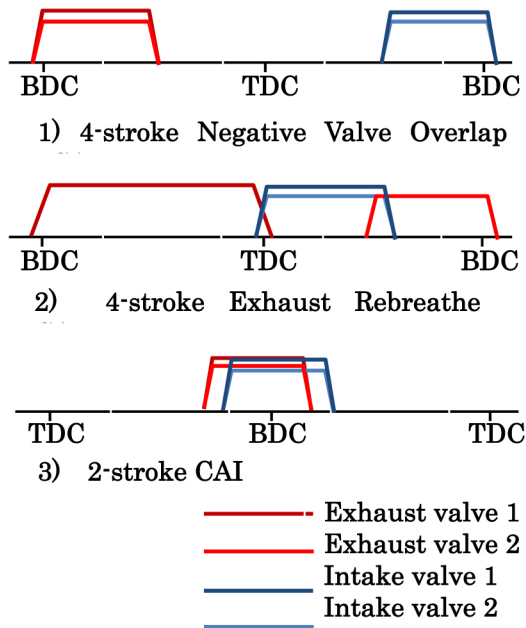


Figure 2. Valve timings for CAI combustion operations

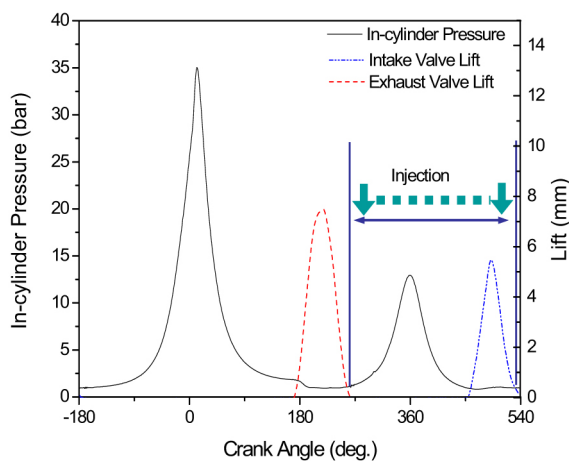


Figure 3. Injection timing in 4-stroke NVO CAI operation

Case 2: 4-Stroke Exhaust Rebreath CAI Operation

Another way to recirculate exhaust gases in the 4-stroke operation is to suck back the exhaust gases from the exhaust pipe by reopening the exhaust valve in the intake stroke. As the electro-hydraulic valve train system installed on the engine allows independent valve control, exhaust valve 1 is actuated to open as normal and exhaust valve 2 is delayed to open during the intake stroke in order to suck the exhaust gas back into the cylinder. In this operation mode, the injection timing is varied from the exhaust valve 1 closure to the intake valve closure, as shown in Figure 4.

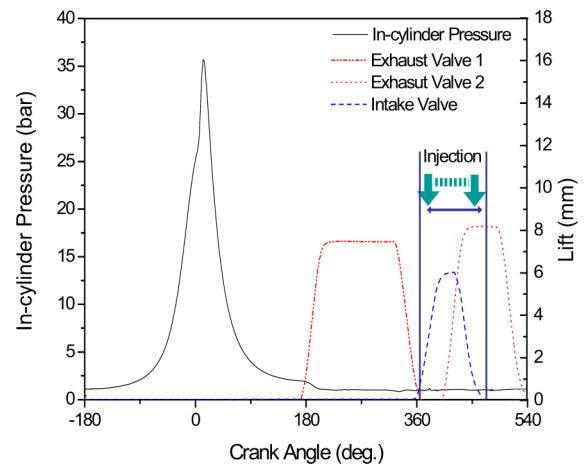


Figure 4. Injection timing in 4-stroke exhaust rebreath CAI operation

Case 3: 2-Stroke CAI Operation

The engine can also be operated in 2-stroke mode by setting the intake and exhaust valves to open and close around BDC. Unlike the conventional crankcase scavenged 2-stroke engine, the scavenging is achieved by boosting the intake air for the poppet valved 2-stroke engine. When the pressurised intake air enters the cylinder, the exhaust gases will be pushed out of the cylinder during the intake and exhaust valve overlap period. In order to retain a portion of the exhaust gases in the cylinder to achieve 2-stroke CAI combustion, the exhaust valve closure is advanced. The injection timing is varied from the exhaust valve closure (-150° ATDC) to the intake valve closure (-100° ATDC), as shown in Figure 5.