

# The Potential of Enhanced HCCI / CAI Control Through the Application of Spray Guided Direct Injection

Simon Brewster, Geoffrey Cathcart and Christian Xavier

Orbital Corporation Ltd.

Copyright © 2008 SAE International

## ABSTRACT

In the current study a single cylinder Spark Ignited engine has been operated in Controlled Auto Ignition mode with centrally mounted spray guided direct injection, employing negative valve overlap to achieve the conditions required for auto-ignition. The injector is a type known in the market and utilises air at elevated pressure to assist preparation of the fuel and delivery of the fuel spray into the combustion chamber. Operation of the injector enables a high degree of control for fuel and air delivery, particularly with regard to stratification of fuel, temperature, air and turbulence within the chamber.

Engine test data show that variation in injection parameters at a fixed engine condition yields high authority over the CAI combustion process. A range of combustion phasing is achieved from 355 to 375 degrees ATDC for the timing of 50% Mass Fraction Burned, whilst the range of maximum pressure rise rate is 70 to 450 kPa / degree. The application of these injection strategies to load range extension enables a Net IMEP of 100 to 700 kPa at an engine speed of 2000 rpm whilst observing a maximum pressure rise rate of 300 kPa / degree.

The ability to vary injection parameters on an individual cylinder and per-cycle basis, coupled with the high authority of this injection system over CAI combustion, indicates a clear potential to address the key issues of CAI operation in a dual-mode SI engine.

## INTRODUCTION

It is considered that the Internal Combustion Engine will remain the dominant powerplant in transportation for at least two decades [1]. At present the ICE utilises either the Spark or Compression Ignition combustion processes. For SI engines, the offering is a cost effective and relatively low regulated emission solution with high power capability, although compromised thermal efficiency. For CI engines, the offering is a high efficiency and high torque solution, although compromised in regulated emissions and cost. A third combustion process receiving wide attention promises to address the efficiency issues of SI engines and the

emission issues of CI engines whilst mitigating aftertreatment complexity and system cost, and therefore may be of considerable significance to the future of the ICE.

This process is characterized by near simultaneous temperature-induced auto-ignition of the charge at numerous sites, and nominal propagation through the chamber [2 - 7]. The process yields significantly lower peak combustion temperatures and in consequence minimal emissions of NO<sub>x</sub>, and at present is considered for both SI and CI engines in dual-mode operation. According to the method of implementation the process has been assigned various descriptions, some of which have been adopted generically. The terms Homogeneous Charge Compression Ignition [5] and Controlled Auto Ignition [7] are common, whilst for CI engines Pre-mixed Charge Compression Ignition [6] is also used. In the following text CAI is employed due to an anticipated level of charge in-homogeneity.

**CAI CONTROL ISSUES** – The significant gains in efficiency and reduction in Nitrogen Oxide emissions offered by the CAI combustion process over conventional SI engines are not yet realized in the market. The remaining technical issues relate to optimal operation within CAI mode, the extent of the CAI operating region, and acceptable transition between combustion modes [8, 9]. It may be considered that these issues centre around the ability to maintain ideal levels of combustion phase and rate of heat release. In addition, for CAI to be feasible in the market, solutions to these technical issues must be achievable within constraints of cost, weight, durability and package.

Combustion phase influences efficiency, regulated emissions, and combustion stability, and is co-variate with rate of heat release [10]. It is in turn a compound function of local charge temperature, pressure, composition and motion. Heat release at higher rates may adversely affect engine noise levels and NO<sub>x</sub> emissions, and at lower rates will be associated with combustion quenching and misfire. Rate of heat release is in turn dependent on local charge temperature, pressure, composition and motion, and is co-variate with combustion phase. The necessity of

mode is then apparent, and the complexity of control arises from the lack of a mechanism to directly adjust phase and rate coupled with the nature of factors determining phase and rate.

Variations in charge temperature, pressure and composition are typical between cylinders of a multi-cylinder engine, causing phase and rate to vary significantly between cylinders [11] and necessitating individual cylinder control. There also exists a strong dependency on conditions in the previous cycle, and in consequence transient operation particularly during mode transition requires management of combustion on a per-cycle basis. The need to control charge state under these conditions contributes to the challenge in switching mode effectively.

In addition, the engine load set-point will affect charge temperature, pressure and according to manifold pressure the capacity to control charge composition in respect of dilution and lambda. Phase and rate are therefore interdependent with load, and CAI operation is consequently load constrained. The upper load limit is determined by excess pressure rise rate and emissions of NO<sub>x</sub>, and the lower limit by combustion instability and misfire. The capacity to modulate phase and rate, ideally on an individual cylinder and per-cycle basis, may therefore determine the extent of the CAI operating region.

**CAI CONTROL SOLUTIONS** – The effective control of combustion phase and rate is being widely addressed by workers in the field, and solutions are being developed in the areas of Engine Management System architecture, combustion sensing, Engine Control Unit hardware and software, and actuation. At first, EMS architecture may partly address the poor feed-forward determinism in combustion phase and hence rate through the use of closed loop combustion control [12], on an individual cylinder and per-cycle basis as required. Such an approach may also serve to improve robustness, enabling tolerance to noise factors such as fuel quality, ambient temperature and system ageing.

Combustion sensing may be achieved through reconstruction of engine speed data [13], direct cylinder pressure measurement [11], charge ionisation measurement [14], engine torque measurement [15], reconstruction of engine vibration measurements [16], or a combination of the above. ECU hardware and operating system software to address the signal and computational processing requirements for individual cylinder cycle-based closed loop control have been widely considered [17, 18]. ECU control strategy is evolving rapidly, and within a framework of torque structure and combustion mode management the complexity of CAI control may be addressed through model based and multi-variable optimal approaches [19, 20].

Whilst potential solutions exist for the EMS in terms of architecture, construction and sensing, it is still the case

that the effective control of CAI combustion phase and rate is constrained by the capacity to alter in-cylinder temperature, pressure, composition and motion on an individual cylinder and per-cycle basis. In addition, the typical co-dependency of in-cylinder conditions creates a strong co-variance of rate and phase, and this limits the extent to which either may be optimized. Hence the area of actuation is perhaps where the greatest challenge remains, and also the greatest opportunity to realize the full potential of CAI combustion in an SI engine. Work in this area may be broadly considered in terms of (i) actuators influencing engine operating parameters, (ii) those affecting air and residual exchange processes, (iii) those related to fuelling, (iv) the application of spark assistance.

Examples of engine operating parameters that may be adjusted to affect CAI combustion include intake air temperature [5], compression ratio [20] and coolant temperature [20]. Actuation mechanisms exist for each of these in some degree, and they may offer an effective method for longer term trim of mean performance. However, the time constant is typically somewhat greater than per-cycle, and the capacity to vary these parameters on an individual cylinder basis is limited. In particular, the implementation of CAI in a dual-mode SI engine with a high compression ratio and highly heated intake air may present challenges for transient response in a typical vehicle. It is indicated that further solutions are required.

Actuators affecting air and residual exchange processes, specifically those determining inlet and exhaust valve motion, are significant in control of CAI combustion through composition, temperature, pressure, motion & in-homogeneity. The high charge temperatures required for auto-ignition are typically achieved through residual trapping [8] and exhaust gas re-breathing [14]. Residual trapping may be effected through reduced intake and exhaust valve lift and duration, giving rise to an extended period of Negative Valve Overlap across the non-firing Top Dead Centre, which accords the description for this approach. In consideration of the need to operate in dual-mode, the NVO strategy may be implemented through the use of twin stage valve actuation [22] or Variable Valve Lift [23], coupled with wide range and fast response Variable Valve Timing to accommodate transient operation.

The NVO strategy is an effective method to achieve CAI combustion, with mechanical variation of valve events allowing a degree of control for phase and rate. However the degree of control is limited in extent, particularly with regard to individual valve, cylinder and per-cycle control. Some additional flexibility may be provided by hydraulic mechanisms introducing additional degrees of freedom [14], and this is an approach which facilitates a degree of re-breathing along with some scope for individual valve, cylinder and per-cycle control. Full flexibility may be provided by an active valvetrain [22], allowing any degree and rate of variation in valve events. However, whilst a significant degree of CAI control is possible with

a complex valvetrain, the market feasibility of such an approach is at present uncertain.

The challenge in actuation may then be understood in terms of a solution enabling a high degree of CAI control, whilst minimizing complexity in the valvetrain. On this basis the potential of fuelling control and spark assistance may be considered, noting that both are capable of variation on an individual cylinder and per-cycle basis. Port Injection has been used widely on SI engines operating in HCCI mode, although it offers limited scope for variation in fuel delivery other than in terms of quantity. Direct Injection, however, enables fuel to be delivered at virtually any point in the cycle. Various studies have been conducted into the effect of DI fuel distribution [8, 11, 14, 24, 25], particularly with regard to injection timing, fuelling on the compression stroke, and fuelling during the NVO event. These studies have shown a strong ability to influence CAI combustion and it is apparent that DI is beneficial in effective CAI control.

Direct Injection may be implemented in several forms, often categorized as wall guided, air guided or spray guided. Whilst wall and air guided systems respectively depend on chamber surfaces and charge motion to prepare the fuel, the spray guided system depends primarily on the injection event itself. Fuel preparation is therefore de-coupled from piston position and charge motion, allowing greater flexibility in injection timing and higher tolerance to lambda variation [26, 27]. It may be anticipated that the higher degree of control over fuel preparation may assist in CAI operation, and in addition the robustness to variation in lambda in SI mode may facilitate effective mode transition through a fuel led strategy.

The application of air-assisted DI may offer particular promise, as the additional degree of freedom offered by the direct injection of air [25] will enable increased control of local oxygen concentration, temperature and charge motion through the cycle. Previous studies employing this injection system [24, 25] and investigating the effect of injection parameters on CAI combustion, have typically demonstrated the effect of injection timing with single injection [24], and in certain instances have explored a part of the additional degree of freedom available [25]. It is considered of value to explore more fully the effects on CAI combustion of air injection duration and decoupling of fuel and air events across the entire range of multiple injection modes available.

The effect of spark assistance on CAI combustion has been reported in the literature [14, 24]. Typically spark assistance may be used to promote combustion stability and advance combustion phase at lower load conditions, and has demonstrated some interaction with the injection mode employed. In addition, the use of spark assistance has been proposed to aid mode transition strategies. The capacity to vary spark events on an individual cylinder and per-cycle basis indicates that spark assistance may be effective in combination with Direct Injection.

**SUMMARY** – It is understood that the effective control of CAI phase and heat release rate represents a primary challenge for the introduction of CAI to the market. Whilst solutions may exist for aspects of control, a key issue remains the capacity of actuators to achieve the necessary authority over CAI combustion. This issue may be interpreted as a requirement for enhanced controllability from fuelling and also ignition systems, enabling a level of CAI control without high complexity in the valvetrain. In this study air-assisted spray guided direct injection is applied to an SI engine operating with a simple NVO strategy. Especially, injection parameters are fully exercised to determine the authority of the system over CAI combustion, and hence the potential for enhanced control.

## EXPERIMENTAL APPARATUS

**ENGINE** – The results that are presented in this paper were obtained from a single cylinder 4-stroke research engine. The base engine specifications are listed below in Table 1. Also the combustion system of this research engine was comprised of a typical 4 valve per cylinder combustion chamber and the Orbital spray guided direct injection fuel system, with the direct injector located near the centre of the combustion chamber.

**Table 1: Single Cylinder Engine Specification**

| Engine                  | Single cylinder                                     |
|-------------------------|-----------------------------------------------------|
| Displacement            | 454 cc                                              |
| Bore                    | 82 mm                                               |
| Stroke                  | 86 mm                                               |
| Number of valves        | 4 Valve, DOHC                                       |
| Compression ratio       | 10.4:1                                              |
| Direct Injector         | Synerject part # 37-163-0004;<br>100 deg.Seat angle |
| Fuel metering injector  | Siemens Deka IV                                     |
| Air injection pressure  | 650 kPa gauge                                       |
| Fuel injection pressure | 720 kPa gauge                                       |
| Piston                  | Flat top                                            |
| EVO                     | 172° ATDC <sub>nf</sub>                             |
| EVC                     | 285° ATDC <sub>nf</sub>                             |
| IVO                     | 435° ATDC <sub>nf</sub>                             |
| IVC                     | 544° ATDC <sub>nf</sub>                             |

For the current work, the Negative Valve Overlap (NVO) method was employed to raise the charge temperature to the level required for reliable auto ignition. Accordingly, base cam shafts were replaced with low lift / short duration cam shafts and were installed on both inlet and exhaust sides of the engine. Also the cam shafts were phased symmetrically about the gas exchange TDC to give an NVO period of 150° CA. This fixed valve timing was maintained throughout this investigation. Engine start up arrangement involved connecting the engine to the motor through the drive

shaft. When starting, the engine was motored to a certain speed and then the fuel injection and spark ignition were switched on. Once the engine is warmed up at the required test speed, in-house developed software enabled spark ignition cut off so that the engine was made to run in CAI mode. Further, to achieve the Stoichiometric condition at higher loads, with the restricted CAI mode cam lifts, external pressure charging was used to supply the additional air to the engine.

Also, the engine was supplied with conditioned air with controlled temperature and humidity. Both coolant and oil were warmed up before acquiring the test data. In-cylinder pressure measurements were obtained using water-cooled Kistler 6061B pressure transducer and these raw pressure data were post-processed to extract all the relevant combustion parameters. Exhaust emissions were measured with an Horiba MEXA 7100 gas analyzer and were used to calculate the overall mixture air-fuel ratio which was further validated by employing the wide band exhaust gas oxygen sensor on the exhaust system.

**DIRECT INJECTION SYSTEM** – The direct injection (DI) fuel system used in the current work comprises an outwardly opening direct injector, a conventional style multi-point port fuel injector and an interface region which provides the path between the air and fuel circuits as shown in Figure 1.

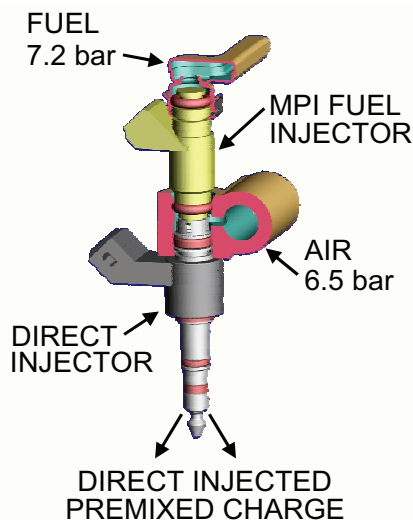


**Figure 1: Schematic of Air-assisted Direct Fuel Injection System**

Since the fuel metering is de-coupled from the direct injection event (Figure 2), the duration and the timing of the direct injection event is essentially independent of the amount of fuel injected into the cylinder. Also the de-coupled fuel metering event results in the mass flux of fuel injected changing during the direct injection event. Besides, the rate of fuel delivery into the cylinder can be changed by changing the delay between the end of fuel metering event and the start of the direct injection event.

A detailed description of this system has been documented in [26].

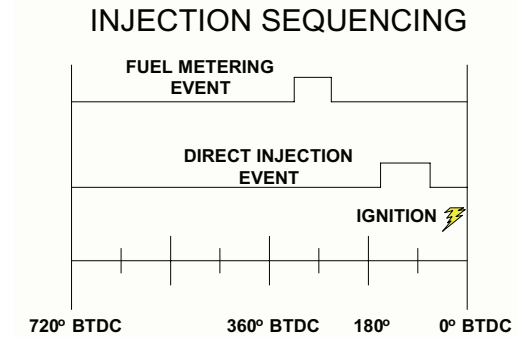


**Figure 2: Schematic of Air-assisted Direct Fuel Injection Events**

By taking advantage of the de-coupling of direct injection event from the fuel metering event, it was possible to implement multiple injections of both fuel metering and direct (air) injector, or the direct injector only (injection of mostly air) into the cylinder at different parts of the engine cycle.

**TEST SCHEDULE** – 98 RON unleaded gasoline was used as the fuel, whilst charge composition was maintained at a Stoichiometric condition, unless otherwise stated in the corresponding discussion.

It should be emphasized that the valve events and lambda were fixed throughout this investigation, as the study was focused on CAI control rather than minimum fuel consumption or emissions for this stage of the research. CAI combustion testing on the single cylinder engine proceeded in the following order.

1. Determination of injection mode and parameter sensitivity on the CAI combustion at 2000 rpm / 300 kPa Net Indicated Mean Effective Pressure (N.I MEP) and Stoichiometric air-fuel ratio.

Table 2 shows the injection modes that were analysed during this current series of tests. Note that the number and timing of fuel metering events is independent of the direct injection events. The system allows for multiple fuel metering events which may be scheduled in order to bias the fuel delivery during the different direct injection events. Timing and duration of direct injection events together with the relative timing of fuel injection events allow for further determination of in-cylinder conditions at intervals during the cycle. Spark-assisted CAI operation was also investigated for each different injection mode. In consideration of all these variables, a total of 39 scans were performed between the 7 injection modes.

**Table 2: Summary of Direct Injection Modes**

| Injection Mode | Direct Injection Event |                        |                      |
|----------------|------------------------|------------------------|----------------------|
|                | NVO                    | Intake Stroke          | Compression Stroke   |
|                | SOI 400–450 deg. BTDC  | SOI 210– 330 deg. BTDC | SOI 60–105 deg. BTDC |
| A              | •                      |                        |                      |
| B              |                        | •                      |                      |
| C              |                        | •                      | •                    |
| D              | •                      | •                      | •                    |
| E              |                        |                        | •                    |
| F              | •                      | •                      |                      |
| G              | •                      |                        | •                    |

- Determination of combustion characteristics with varying load at fixed engine speed and fixed injection mode, followed by application of different injection modes to achieve highest and lowest load at fixed speed, while controlling the maximum pressure rise rate below 300 kPa / deg.CA.
- Determination of combustion characteristics in response to transient injection mode switch.

## RESULTS & DISCUSSION

**FIXED LOAD** – The effects on CAI combustion with variation of injection mode and parameters are illustrated at 2000 rpm, 300 kPa N.IMEP and stoichiometric air fuel ratio.

**Parameter Scan** – At first a scan is presented using injection mode B (Table 2) to illustrate the effects of change in injection parameters at a single injection mode.

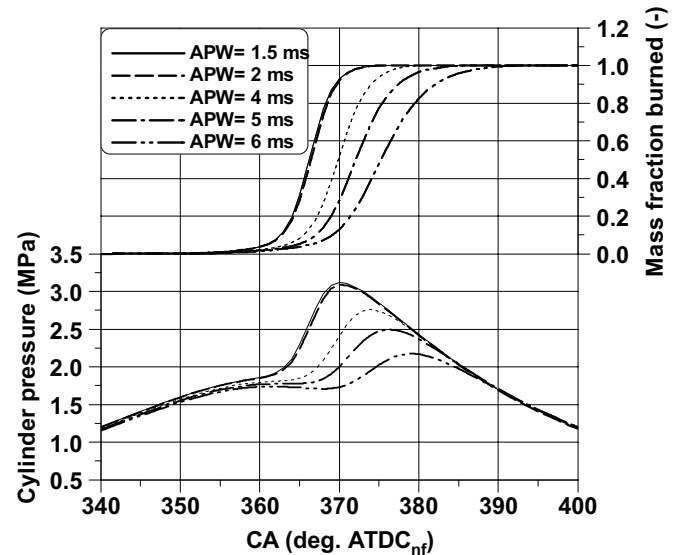


**Figure 3: Variation in Cylinder Pressure as a Function of Injector Air Pulse Width**

Figure 3 shows the results of varying direct injection pulse width (APW) with a constant start of injection at stoichiometric A/F ratio. It can be seen that increasing the direct injector air pulse width delays the combustion event resulting in retarded peak pressure locations. As the injection pulse width is increased, the end of injection becomes later when the start of injection timing is constant. The later end of injection timing reduces mixing time for the injected fuel, which can lead to increased in-homogeneity within the cylinder. As well, when the injection pulse width is increased, the quantity of injected air also increases, which can act as a charge cooling mechanism for the mixture. It is considered that these two effects are responsible for the retarded combustion phasing which is evident with increased direct injection pulse width.

Figure 4 shows the effect of increased direct injector pulse width on relevant combustion parameters. Since the combustion phasing is retarded with increasing direct injector pulse width, a greater portion of the combustion heat release occurs during the period where cylinder volume increases, resulting in reduced peak cylinder pressures as well as the lower pressure rise rates. Combustion stability (expressed as COV of Net IMEP) is found to deteriorate as injection pulse width is increased beyond 5 ms as the combustion phasing becomes very retarded.