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An OCP Four-Stroke Vehicle Application – *A Practical Study of the Strategies for Future Fuel Consumption and Emissions Solutions*.

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ABSTRACT

Direct injection spark ignition engines offer the potential for large reductions in fuel consumption due to ultra-lean operation. This fuel consumption reduction, however, can come at the cost of higher engine emissions levels which are difficult to catalyze in the lean environment. Recent vehicle development at the Orbital Engine Company in Perth, Australia, using air assisted DI technology, has demonstrated the ability to achieve European Stage 3 emissions levels with a single under-body 3-way catalyst with aged catalysts, and European Stage 4 with fresh catalysts.

INTRODUCTION

The direct injection (DI) spark ignition engine can reduce specific fuel consumption at light loads due to the ability to run stratified charge combustion, and hence overall very lean air/fuel or dilution ratios (1,2[*]). However, many of these systems suffer from increased raw engine emissions levels due to the stratification process, leading to increasing dependence on very high catalyst conversion efficiencies. Coupled with the lower exhaust temperatures and lean environment, the adequate post treatment of this increased level of exhaust emissions becomes difficult in comparison to conventional port injection engines. Due primarily to the extent of lean operation, the after-treatment system required for the typical direct injection, lean burn engines becomes complex and expensive, with the most likely choice being the lean NOx storage and release system. These systems, although offering potential high NOx conversion efficiencies, suffer from rapid degradation due to sulfur poisoning with the current levels of sulfur in commercial fuels.

The Orbital Combustion Process (OCP) using a combination of air-assisted direct fuel injection with a spray or jet-guided combustion system demonstrates the ability to simultaneously achieve large reductions in fuel consumption with low hydrocarbon and oxides of Nitrogen emissions levels. This combination lends itself to a strategy being adopted, whereby the engine-out (or raw) emissions levels (particularly NOx) are reduced sufficiently at low loads so as not to rely on the need for high after-treatment conversion efficiencies during lean operation. At the higher loads, the engine is run at stoichiometry in order to utilise the high efficiencies provided by conventional 3-way catalyst systems.

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[*] Figures in brackets indicate reference number.

SYSTEM INSTALLATION

The vehicle used for the development work was a 1998 specification Ford Mondeo, with a 2.0L DOHC 4V Zetec engine. The intertia test weight for this vehicle is 1360kg. This combination of vehicle weight and engine displacement was chosen to be representative of what is believed to be typical potential European applications of direct injection technology. Table 1 outlines the specifications of the baseline MPI vehicle and the modified OCP DI vehicle. The comparison was made with minimum changes to the base vehicle specification. The same transmission, gear ratios, and idle speed were used in order to gain an understanding of the benefit of direct injection alone. An area of note is the use of the standard inlet system and exhaust manifold, with no modification to the base engine inlet flow induced in-cylinder air motion. The engine control unit (ECU) used for the demonstration was Orbital's own development ECU. This ECU is not intended as a production unit, but does, however, offer a high level of flexibility in order to develop new strategies in short time frames.

The air-assisted direct injection fuel delivery system consists of 3 main components. These are a fuel delivery injector as per standard port fuel injection systems, a direct (or charge) injector, and an interface region which joins the two. Typical operation of the system involves a fuel metering event, whereby the fuel injector delivers the fuel into an interface region using a constant pressure differential of normally 1.0 to 1.5bar. A mixture of fuel and air is then delivered directly to the combustion chamber through the direct injector at a nominal pressure of 6.5bar. This operation effectively de-couples the fuel metering event from the direct injection event. This independence of the two events allows the fuel delivery profile into the cylinder to be tailored at each operating condition. The injection duration and phasing between the fuel metering event and direct injection event allow greater control of the stratification process across a wide range of speeds and loads.

The injected air is supplied to the air rail via a single cylinder reciprocating piston compressor. Air pressure is maintained at 6.5bar via the use of an inlet throttle on the compressor. This throttle is controlled by the ECU via feedback from an air rail pressure sensor. The incorporation of this throttle not only removes the requirement for a mechanical air pressure regulator, it also helps to reduce the parasitic of the compressor at low load operation. At low loads, the injected air quantity is typically half of what is supplied from the compressor, when the compressor is sized according to maximum air usage which occurs at the higher loads. Therefore, by throttling the compressor to reduce the airflow, there is a reduction of the air pumping work.

The fuel system used for the demonstration vehicle also incorporated the canister vapour purge through the air compressor. This allows the fuel vapour to be drawn from the canister into the air circuit of the fuel system, and thus injected directly into the combustion chamber along with liquid fuel and air as per standard operation. The injected fuel vapour then remains in the fuel-rich region of the stratified charge. This enables the engine to continue operating in a stratified condition, without increasing engine raw hydrocarbon emissions. Incorporating the CVP into the compressor inlet is optional for the OCP system, depending on the type of operation and whether the potential benefit of running lean stratified operation while purging is warranted. In cases where it is not, a more conventional system, whereby the canister vapour is purged through the inlet manifold can be used.

The inlet system incorporates an electronic throttle. This allows operation at very lean A/F ratios as well as switching to stoichiometric operation at the higher speeds and loads encountered. There are no other controls of inlet flow dynamics, for example for modifying swirl or tumble.

The exhaust system used for the DI application was very similar to that for the MPI vehicle. This consisted of a cast iron exhaust manifold flexibly coupled to a single-skinned downpipe feeding an underbody catalyst located some 1.3 meters from the cylinder head exhaust manifold flange face. Working in conjunction with Johnson-Matthey, a 3-way catalyst formulation was chosen. The catalyst system consisted of two separate race-track type catalyst bricks, with a total volume of approximately 2.0 litres. Table 2 outlines the specifications of this catalyst system.

Catalyst Designation	JM 370
PGM Ratio (Pt/Rh)	10:1
PGM Loading	110 g/ft^3
Cell Density	400 cells/in^2, 6 mil
Volume	2.04 Liters (total of two bricks)

Table 2 Catalyst Specification

Low NOx emissions in conjunction with low fuel consumption requires the use of high levels of EGR. The standard MPI EGR system was replaced with a high flow design incorporating electronically controlled EGR valves. The DI vehicle exhaust system also incorporated a lambda sensor. This was only a switching type sensor as per the standard MPI vehicle specification. The lean, stratified operation for this demonstration vehicle was performed with open-loop air/fuel ratio control.

VEHICLE DRIVE-CYCLE RESULTS

In order to achieve the maximum fuel consumption reduction in vehicle applications, it is imperative that the injection and combustion system allows lean, stratified operation from starting, including the entire warm-up period from ambient start conditions. The plot of A/F ratio through an ambient start MVEG-B drive cycle test, shows that after a rapid catalyst warm-up routine, the engine operation switches directly to lean, stratified operation. The first phase (or ECE 15 test) is predominantly run with lean stratified operation with high levels of EGR, the EGR content increasing as the engine warms up through this first phase. This ensures that a significant fuel consumption saving is made in the first phase, while also controlling the NOx emissions to low levels. The second phase, however, includes substantial periods of stoichiometric operation. The higher engine loads and speed experienced in the second phase of the drive cycle make it difficult to achieve NOx emissions which are low enough not to rely on sufficiently high catalyst conversion efficiences. For this reason, the engine switches modes at these higher load regions, to stoichiometric operation with EGR, in order to take advantage of the high NOx conversion efficiencies offered with current 3-way catalyst technology. Relatively high levels of EGR are still used during this operation in order to reduce raw NOx emissions and hence catalyst burden, as well as improve the fuel economy through some reduction in pumping work.

Raw (Engine Out) Emissions

Comparing the raw emissions level of the drive cycle show how well the emissions are controlled with the air-assisted direct injection system. The hydrocarbon (HC) emissions are lower than the MPI equivalent over the first phase. This is due to a combination of the emissions reduction due to cold start operation, as well as reduction in the HC emissions during low load operation for the DI vehicle. Indeed, it has been demonstrated that the air-assisted direct injection combustion system has the ability to reduce HC emissions compared with MPI operation even at normal operating temperature (3). The second phase shows a small increase in HC emissions for the DI operation vehicle. This is primarily due to high levels of EGR employed for the higher load, higher speed operation in this part of the drive cycle. The combined MVEG-B drive cycle result shows comparable HC emissions are achieved with the MPI and the DI vehicles. This result for the DI vehicle is particularly impressive when considering that it is in combination with substantial reductions in NOx emissions. From the NOx emissions summary, it can be seen that for the DI vehicle operation, a combined cycle raw NOx emissions level of only 0.25g/km is achieved. The achievement of these low engine-out emissions levels aid to reduce the requirement of the after-treatment system.

Exhaust Feedgas Temperatures

One critical element of achieving low tailpipe emissions, especially when using an underbody catalyst system, is rapid heating of the catalyst from an ambient starting condition. An Orbital patented fast catalyst “light-off” routine was employed in order to achieve maximum catalyst conversion efficiencies in the shortest possible time. The feedgas temperature modal plot shows the temperature as a function of time from starting, measured approximately one meter from the cylinder head exhaust manifold gasket face. A feedgas temperature of over 570^{o}C is achieved during the first 10 second idle period. This rapid heating ensures that conversion efficiencies, especially for hydrocarbon emissions, are high shortly after starting. The exhaust temperature is maintained at a reasonable level throughout the drive-cycle, with an average temperature of approximately 280^{o} Celsius during the first phase of the cycle. This temperature, coupled with lean operation, results in high conversion efficiencies of HC emissions throughout the drive-cycle.

Tailpipe emissions

The tailpipe emissions were measured on the MVEG-B drive cycle using the 3-way catalyst system as outlined in Table 2. The particular catalyst set used for the test results presented had accumulated some 25,000 kms of vehicle aging, all with fuel sulphur levels of approximately 150 PPM. With this aged catalyst, the vehicle still achieved emissions levels which are significantly less than the European stage 3 levels, indicating the possibility to satisfy the emissions durability requirement of European stage 3 legislation. The margins are sufficiently large that the emissions levels are actually below the proposed European stage 4 levels.

It should be remembered that these tailpipe emissions levels were achieved with a single, underbody 3-way catalyst, including an exhaust system incorporating a cast iron manifold. It is believed that with further calibration refinement and/or exhaust system optimisation, including reduced thermal inertia of the system, an increased margin, particularly for HC emissions, will be able to be achieved compared with the proposed European stage 4 emissions levels.

Fuel Consumption Reduction

The table containing fuel consumption results outlines the cycle fuel consumption comparison between MPI and OCP DI vehicles. The direct injection equipped vehicle achieved a reduction of over 10% in fuel consumption over the drive cycle compared with the MPI baseline. The majority of the fuel savings were achieved during the first phase, which contains the highest proportion of low load operation. During the first phase, the fuel consumption was reduced by some 16.8% compared with the MPI baseline. Due to the adoption of significant stoichiometric air/fuel ratio running, there was little reduction in the second phase of fuel consumption.

The MVEG-B drive cycle was also performed with the two vehicles fully warm. The comparison for this hot-start condition shows further reductions in fuel consumption for the DI vehicle when compared to the MPI vehicle under the same hot-start conditions. Much of this further reduction is due to the reduction in the average indicated load, which corresponds with areas of increasing advantage in terms of fuel economy for the DI engine in comparison to the MPI engine. The reduction in first phase fuel consumption becomes 25% compared to the MPI level, with a total reduction over the drive cycle of 13.5%. As expected, the fuel consumption reduction in the second phase remains relatively unchanged. This is due to the second phase being close to fully warm in a standard ambient start test, as well as the large periods of operation at stoichiometry for the DI vehicle where little advantage in fuel economy is provided.

The reduction in indicated load for the hot-start tests is due to reduced engine and drivetrain losses. As the engine and drivetrain temperatures increase, the friction due to these components decreases. The figure shows the engine oil temperature for an ambient start condition for MPI and DI vehicles. From this figure, it can be seen that for an ambient start condition, the oil temperature and thus the base-engine friction levels are similar throughout the drive-cycle for both MPI and DI engines. As the oil temperature increases, the engine friction level reduces, and therefore the indicated load for a given brake load reduces. As this indicated load reduces, the advantage offered by lean operation DI increases. The A/F ratio modal plot is a good indicator of this also. It can be clearly seen that progressing through the drivecycle, the same speed and load conditions are run with increasingly lean A/F ratios. This is because as the load reduces, the demand A/F ratio increases according the calibration of the engine. The comparison between ambient and hot start drive cycle results shows that there is a large potential to further reduce the fuel consumption for the OCP DI vehicle, by reducing the high friction levels associated with ambient start conditions through improved lubricant warm-up. This potential further reduction in fuel consumption when compared to the similarly reduced friction MPI engine will only be fully realised for systems which offer the ability to run lean, stratified combustion throughout the engine warm-up period.

When comparing engine coolant temperatures, the effect of the higher indicated thermal efficiency of the DI engine operation becomes apparent. The engine coolant takes significantly longer to warm up than with MPI operation. This is due to the more efficient combustion process, with less heat input to the combustion chamber walls. The slower heating of the combustion engine coolant is not thought to be a major contributor to the fuel consumption differences between ambient and hot start drive cycle results. Although some small changes in the engine calibration results from warm-up conditions, the oil temperature effects of higher friction for low temperatures however, is believed to be a significant contributor to the difference between ambient and hot results.

Independent Validation

In order to validate the drive cycle results achieved at the Orbital Engine Company’s facilities, the DI vehicle was tested at an independent emissions laboratory. RWT ÜV Fahrzeug GmbH, the technical service responsible for exhaust emissions in Germany, performed measurements on the OCP demonstration vehicle fitted with a fresh catalyst. The results confirm those measured at Orbital, with very low emissions levels evident with the fresh underbody 3-way catalyst. The levels were significantly below the proposed European stage 4 levels.

DISCUSSION

Vehicle development at the Orbital Engine Company, and subsequent testing at an independent European emissions laboratory, has confirmed the theory that the air-assisted direct injection combustion system applied to 4 stroke gasoline engines can achieve European Stage 3 emissions levels with the use of an underbody 3-way catalyst system only. This offers the potential to reduce the after-treatment cost. The after-treatment system, if not reduced, looks set to contribute highly to the cost of introducing spark ignition direct injection engine technology in this time of increasingly stringent vehicle emissions legislation. The emissions levels measured using a 3-way catalyst system are low enough to indicate the possibility of meeting the European stage 4 emissions levels. In combination with these levels of emissions, the vehicle fuel consumption has been reduced by some 10% in comparison with the MPI baseline vehicle.

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