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186 Improving Robustness of Spray Guided DI Combustion Systems: The Air-Assisted Approach

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Although the direct injection gasoline engine offers the potential for large fuel consumption reductions in passenger vehicles, the wide spread adoption of this technology has been slow. With the onset of ever increasingly stringent emissions legislation requiring the reduction of exhaust pollutants, the DI combustion system for the future must therefore exhibit the favourable combination of significant fuel consumption reduction with low engine emissions levels in a vehicle environment. The spray guided combustion system has been shown to provide perhaps the best potential to deliver the fuel consumption reduction and low emissions levels required of the advanced concepts, but must overcome shortfalls of reportedly high sensitivity to operating parameters including injection and ignition timing. The Orbital air-assisted fuel system has unique properties in the manner in which the fuel is delivered into the combustion chamber, specifically the time varying flow rate of fuel injected during the direct injection event. By managing this instantaneous fuel flow rate through the direct injector, it is shown that the air-assisted system, when applied to a spray guided combustion system, has the ability to achieve low fuel consumption and emissions levels, combined with reduced sensitivity to variation in ignition and injection timings to achieve a robust combustion system.

***Keywords*: IC Engines, Gasoline Direct Injection, Spray Guided**

1. Introduction

The gasoline direct injection, stratified charge engine offers the automaker the potential for large reductions in vehicle fuel consumption due to the ability to operate at high dilution ratios at part load. Unfortunately, the very concept of stratified operation results in a charge that has both temporal and spatial variation of fuel concentration, with the requirement that at some time and location, an ignitable mixture concentration exists in order to promote an effective combustion event. While this concept sounds simple enough, the inhomogeneous nature of DI stratified combustion systems leads to some major challenges in the operation of these engines. Not the least of these challenges, is achieving robust engine operation, which tolerates changes in ignition and injection timings, total air to fuel ratio and EGR rates. This combustion robustness is a key consideration when selecting and developing direct injection combustion systems for the ease of implementation to real world vehicle application. Not surprisingly, there is a strong interdependence of the combustion and fuel injection system. This paper focuses on the injection system characteristics required for achieving a greater level of robustness, in particular the requirements for a spray guided, lean stratified combustion concept.

2. Spray Guided Combustion Systems

The spray guided DI combustion systems, whereby the fuel is injected towards the spark gap location directly from the injector, were amongst the first to be investigated for the application on gasoline 4-stroke automotive engines (1). However, early studies showed that these systems typically suffered two main problems, these being spark plug fouling and poor combustion robustness (2). Due to these problems, the wall guided and/or air guided combustion systems were developed, whereby the fuel is injected a considerable distance from the spark plug and carried to the spark plug by a secondary mechanism. The combined effect can lead to a combustion system that overcomes the high sensitivity to ignition and injection timings and reduces spark plug durability concerns. Indeed, the current commercial introduction of stratified DI 4-Stroke gasoline engines has been comprised solely of these wall and air guided combustion systems (3,4). However, it seems that many of these combustion systems typically suffer from increased engine-out emissions, especially unburnt hydrocarbons (HC) emissions. As emissions legislations worldwide are becoming increasingly stringent, there is a need to have a combustion system that not only reduces fuel consumption, but also minimises engine out emissions. For this reason, there is a general increase of interest and activity on spray guided combustion systems for introduction on the next generation of automotive DI gasoline engines (5,6).

In order to achieve good burn rates throughout the combustion event and minimise HC emissions in a DI stratified charge engine, a strong air/fuel ratio gradient is required at the boundary that separates the combustible mixture from the remainder of the cylinder contents. The mixture near the spark plug should show the opposite trend at times typical of ignition, with low air/fuel ratio gradients, with the mixture strength in the ignitable range to promote large ignition windows and hence a robust combustion system. The spray guided combustion system concept has the fuel spray injected towards the ignition source directly from the fuel injection source and typically has close spacing of the injector and spark location. This promotes in most systems rapidly changing fuel concentration gradients as the fuel passes the spark location during the injection period, and hence the reported problem of poor robustness. In order to reduce these concentration gradients and address one of key concerns with spray guided systems, some different approaches are required. One such approach is the adoption of an air-assisted injection system, such as the one developed by the Orbital Engine Company. This system has the ability to vary the instantaneous injected fuel flow rates which make it ideally suited to the spray guided combustion system, thus offering large reductions in fuel consumption and raw NOx emissions, while minimising HC emissions all in a robust operating environment (7,8).

3. Air Assisted Injection System

The air assisted injection system is comprised of two main components, a fuel metering injector similar to a port fuel injector, and an air or charge injector, which delivers a mixture of metered fuel and air into the combustion chamber. This system has been reported previously to exhibit the favourable qualities of small fuel droplet size and low penetration rates during compression stroke injection (7). A unique feature of the system is the decoupling of the direct injection event with the fuel metering event. This allows the direct injection event to be tailored to what is required by the combustion, rather than being limited by also needing to perform the fuel metering function, as is the case in high pressure single fluid injection systems. Figure 1 shows the components comprising the air-assisted injection system as well as a typical injection scheduling schematic that illustrates the de-coupling of the fuel metering from the direct injection event.

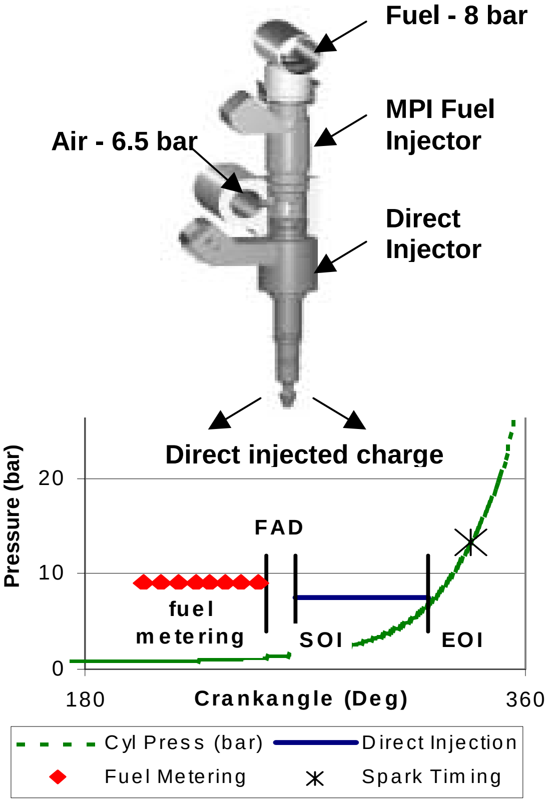

Figure 1. Injection system components and typical sequence of injection event

Due to this sequence of events, the fuel flow rate during the direct injection event is not constant. With adjustment of the total direct injection duration as well as the delay period between the fuel metering event and the direct injection event (FAD), the instantaneous fuel flow within the direct injection event can be varied.

Figure 2 shows a typical fuel flow curve for the air-assisted system compared with the same total fuel level of a comparable high pressure, single fluid injector. These were measured with a rotating rig consisting of a high number of discrete tubes that capture the injected fuel during different times of the injection event.

Comparing the instantaneous flow rates of the two injection systems, the differences are very noticeable. The single fluid system displays the typical near square wave response that would be expected of a fixed area incompressible flow device. The air-assisted system has a much longer spread of fuel, with a relatively high flow rates near the beginning of the injection event, with lower fuel flow rates near the end of the injection event. The lower fuel concentration gradients formed due to this extended duration with low fuel flow rates is considered to be very important to realise a robust spray guided combustion system.

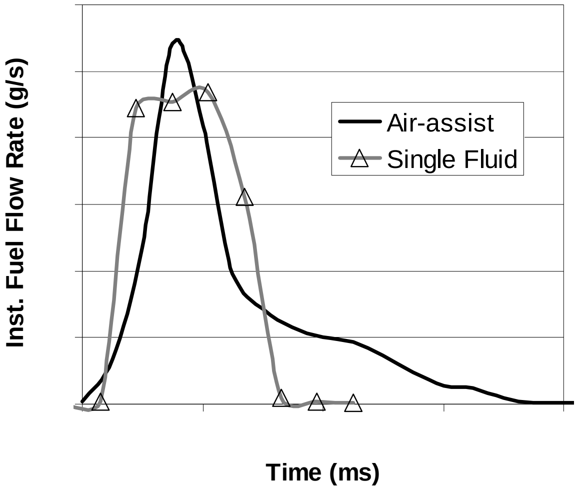

Figure 2. Comparison of instantaneous mass flow rates of air-assisted injection system and high pressure, single fluid injector.

4. Effect of Instantaneous Fuel Injection Flow Rates

Single cylinder engine tests were designed in order to demonstrate the effect of altering the fuel flow rates into the combustion chamber. The testing compared typical lean stratified engine operation with two distinct instantaneous injected fuel flow curves. By altering the air assisted injection parameters of direct injection duration and the period between the fuel metering and direct injection event, the instantaneous fuel flow rate at any given time within the injection event can be altered. Testing was conducted with injection timings typical of air-assisted spray guided combustion system calibration, as well as a more compact fuel delivery profile. Figure 3 shows the difference in the fuel flow rates during the injection event measured injecting into atmospheric conditions. Small changes will result when injecting into rising cylinder pressure, however, the trends will be similar and the atmospheric conditions are used to illustrate the differences able to be achieved with the air-assisted injection system.

As can be seen in Figure 3, the typical injection timings result in a longer fuel delivery period, with a characteristic fuel lean period during the latter half of the injection duration. The more compact fuel delivery shows a shorter total time period for delivery of the fuel, higher peak flow rates, with a sharp end of fuel delivery profile. The compact fuel delivery profile lacks the same long fuel lean period characteristic of the typical fuel profile. The longer fuel delivery period with a fuel lean area late in the injection event is considered to be important for reducing the fuel concentration gradients in the region near the spark plug for a spray guided combustion system.

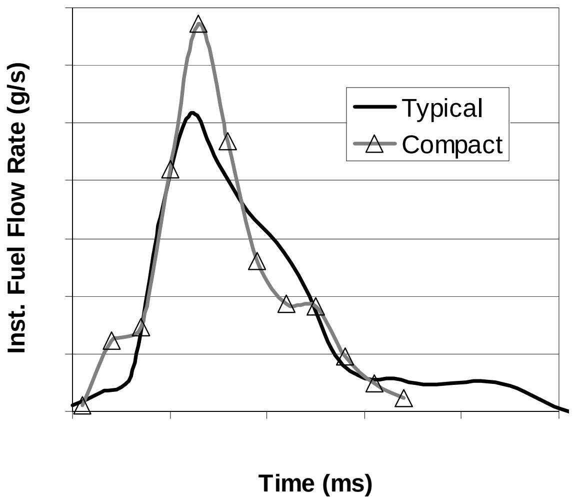

Figure 3. Instantaneous fuel flow rate comparison of typical air-assist operation and compact fuel delivery

The engine results are from a single cylinder research engine fitted with an air-assisted injection system and having a combustion chamber configuration including piston bowl typical of that for the Orbital Combustion Process (OCP) as applied to 4 Stroke engines (7).

The engine was operated at 1500rpm, and approximately 8.4 mg/shot injected fuel flow rate. The calibration used was typical of that required in the vehicle application, with a lean stratified operation and high levels of EGR to reduce the engine out NOx emissions while achieving low fuel consumption. For each set of injection parameters, the start of direct injection (SOI) and ignition timing were optimised to establish the base calibration point. The air/fuel ratio and EGR rates were constant for both sets of injection timings. Table 1 shows the summary of operation for each of the two distinct flow profiles. At the nominal calibration set point, the fuel consumption and emissions are found to be similar for the two calibrations, with both displaying low NOx emissions and good HC control, especially for the typical fuel delivery profile.

Fuel Profile	Typical OCP	Compact
N.IMEP (g/kWh)	212.2	212.9
ISFC (g/kWh)	230.4	230.5
ISHC (g/kWh)	5.1	6.0
ISNOx (g/kWh)	1.2	1.1
Smoke (FSN)	0.04	0.03
A/F Ratio (:1)	31.0	30.8
EGR Rate (%)	41.0	41.2

Table 1. Base calibration operation comparison

Once the base calibration point was established, a timing matrix was performed of ignition and injection timing combinations within an 8-degree crank angle region.

Figure 4 and Figure 5 show the net indicated specific fuel consumption of the typical and compact fuel profiles respectively for the matrix of ignition and injection timings relative to the nominal calibration. For these figures, the base calibration point corresponds to the origin (0,0) with the ignition and injection offsets being positive for increased advance and negative for more retarded settings relative to the base calibration. The standard fuel profile shows a large area with little change in fuel consumption with changes in the ignition and injection timings. The corresponding plot for the compact spray pattern shows a higher sensitivity, with a large area where the fuel consumption has risen to over 245 g/kWh. This increase in fuel consumption is predominantly due to instability encountered in these regions, as shown in the figures below.

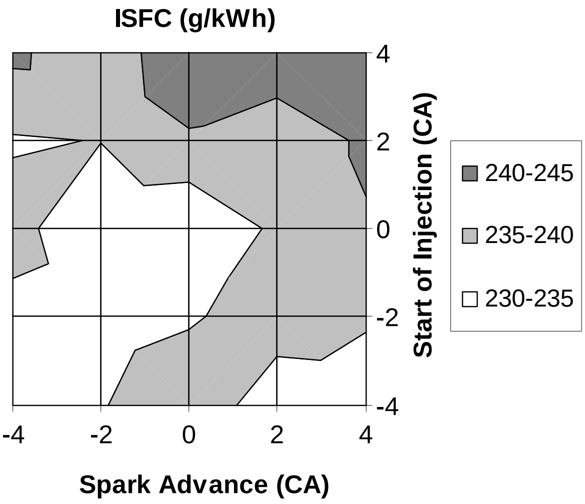

Figure 4. Net indicated specific fuel consumption with typical air-assist injection profile

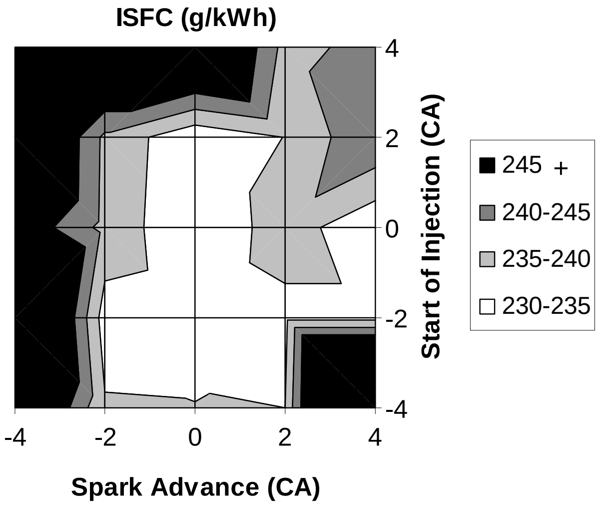

Figure 5. Net indicated specific fuel consumption with compact fuel delivery profile.

Comparison of the combustion stability represented in Figure 6 and Figure 7 as standard deviation of net IMEP shows distinct differences between the two fuel profiles. The typical fuel profile displays the favourable characteristic where the combustion variation of IMEP remains predominantly at a level less than 0.15 bar, with no misfires present over the complete matrix of ignition and injection timings. The compact fuel flow profile is more sensitive to ignition and injection timings, with the combustion stability becoming unacceptable over a significant range of ignition and injection timings away from the base calibration. The shorter fuel delivery duration with higher peak fuel concentration rates and steeper fuel delivery profile near the end of the injection period reduces the combinations of ignition and injection timings where a consistently ignitable mixture is present. The comparison of the combustion stability best presents how the air-assisted injection system can promote reduced sensitivity of ignition and injection timings by effectively increasing the fuel delivery period into the combustion chamber, in such a way as to promote lower air/fuel ratio gradients in the region near the spark plug at time of ignition.

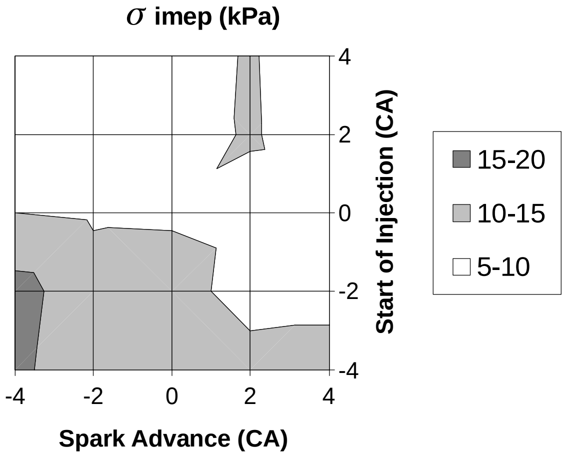

Figure 6. Combustion stability matrix for standard fuel injection profile

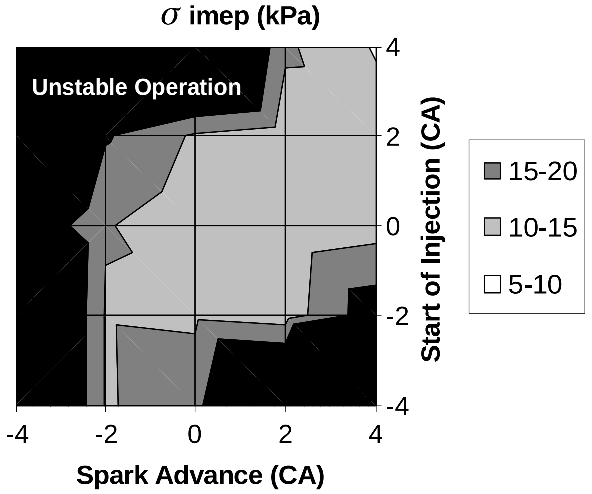

Figure 7. Combustion stability matrix for compact fuel injection profile

In summary, the results show that when each distinct fuel delivery profile is optimised for ignition and injection timings, the performance is very similar, with low fuel consumption and emissions demonstrated. However, when the ignition and injection timings are altered from the base calibration, the two profiles show very different behaviour. The typical timings show good robustness at lean A/F ratios and high EGR rates, whereas the compact profile shows significantly higher sensitivity to ignition and injection timings, with poor combustion stability exhibited when the calibration is moved from the optimised point. Combustion system robustness is a considered to be an important characteristic for easy transfer to a multi-cylinder and ultimately to the vehicle environment, and therefore needs to be included in any analysis of a combustion system.

5. Conclusions

Testing of the air assisted spray guided direct injection system developed at Orbital has demonstrated that significant improvements can be made to the robustness of engine calibration by control of both the duration and the fuel flow rate present during the direct injection event. These controls allow minimisation of the air fuel gradient present at the spark plug gap at and about the time of ignition and hence an increase in both the spatial and temporal tolerance to the location of the ignitable mixture when compared to a more compact fuel delivery profile.

While similar fuel consumption and emissions were able to be obtained from both the relatively longer injection duration typical of Air Assist and a more compact fuel injection profile, the calibration sensitivity of fuel consumption and combustion stability were significantly higher for the compact fuel delivery profile. This result emphasises that as the search for the second generation DI gasoline engine continues, it is important not only to compare the specific fuel consumption and emissions at the nominal calibration, but also to understand how these may be adversely influenced by subtle changes to the calibration. This is a critical step in the ease of implementing the combustion system into a successful production vehicle environment.

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