SAE TECHNICAL PAPER SERIES

2002-01-0705

Application of Air Assisted Direct Fuel Injection to Pressure Charged Gasoline Engines

Geoffrey Cathcart and John Tubb
Orbital Engine Co.

Reprinted From: Direct Injection SI Engine Technology 2002
(SP–1693)

The Engineering Society
For Advancing Mobility
Land Sea Air and Space®
INTERNATIONAL

SAE 2002 World Congress
Detroit, Michigan
March 4-7, 2002

400 Commonwealth Drive, Warrendale, PA 15096-0001 U.S.A. Tel: (724) 776-4841 Fax: (724) 776-5760

The appearance of this ISSN code at the bottom of this page indicates SAE's consent that copies of the paper may be made for personal or internal use of specific clients. This consent is given on the condition, however, that the copier pay a per article copy fee through the Copyright Clearance Center, Inc. Operations Center, 222 Rosewood Drive, Danvers, MA 01923 for copying beyond that permitted by Sections 107 or 108 of the U.S. Copyright Law. This consent does not extend to other kinds of copying such as copying for general distribution, for advertising or promotional purposes, for creating new collective works, or for resale.

Quantity reprint rates can be obtained from the Customer Sales and Satisfaction Department.

To request permission to reprint a technical paper or permission to use copyrighted SAE publications in other works, contact the SAE Publications Group.

GLOBAL MOBILITY DATABASE

All SAE papers, standards, and selected books are abstracted and indexed in the Global Mobility Database

No part of this publication may be reproduced in any form, in an electronic retrieval system or otherwise, without the prior written permission of the publisher.

ISSN 0148-7191
Copyright © 2002 Society of Automotive Engineers, Inc.

Positions and opinions advanced in this paper are those of the author(s) and not necessarily those of SAE. The author is solely responsible for the content of the paper. A process is available by which discussions will be printed with the paper if it is published in SAE Transactions. For permission to publish this paper in full or in part, contact the SAE Publications Group.

Persons wishing to submit papers to be considered for presentation or publication through SAE should send the manuscript or a 300 word abstract of a proposed manuscript to: Secretary, Engineering Meetings Board, SAE.

Printed in USA

2002-01-0705

Application of Air Assisted Direct Fuel Injection to Pressure Charged Gasoline Engines

Geoffrey Cathcart and John Tubb
Orbital Engine Company, Australia.

ABSTRACT

With the ever increasing desire to improve the thermal efficiency of the internal combustion engine, the combination of gasoline direct injection with engine downsizing and intake charging may offer the greatest potential for maximizing the efficiency of these engines. Although the comparative benefit of direct injection alone may be reduced when compared to the downsized and charged engine directly, the combination of the two technologies has the potential to offer substantially larger total fuel consumption reduction in automotive applications than either technology independently.

The Orbital developed air-assisted spray guided combustion system has unique properties which are shown to be desirable given the increased demand of boosted engine operation. The decoupling of fuel metering and direct injection events promotes large dynamic range of fuel metering and, when combined with variable fuel metering differential pressure, results in turn down ratios in excess of 24 to 1. As well, the spray guided combustion system, with the drect injector aligned with the cylinder bore axis, enables injection timing which is not dependent on piston position. This results in the ability to operate the engine with boosted inlet conditions at higher part load, leading to further reductions in fuel consumption compared to naturally aspirated operation without increasing engine out emissions levels.

INTRODUCTION

The air-assisted spray guided direct injection combustion system has demonstrated the ability to significantly reduce fuel consumption in four stroke vehicle applications, while simultaneous meeting some of the most stringent future emissions legislations [1,2]. With the aim of many automakers to further improve the efficiency of gasoline engines to approach that of modern high technology Diesel engines, the combination of direct injection with engine intake charging may offer the most potential to do so. This combination, however, introduces new challenges, as the demand on the fuel system and combustion system of a direct injected pressure charged engine is increased due to the following.

- Higher turn down ratio of the fuel injection system needed (greater dynamic range of the fuel metering required).
- Short injection time available to deliver very high quantity of fuel (more than 100 mg/injection event in some applications) into the combustion chamber at full load, high engine speeds.
- Increased cylinder pressures during boosted operation reducing differential pressure across injection system.
- Quiescent chamber preferable for high load operation to reduce combustion harshness.
- Low port restriction to improve flow efficiency to minimize the boost level required for a specified output.

The compatibility of the air-assisted, spray guided direct injection system with charged engines has been questioned in respect of these increased demands, as well as the ability of such a relatively low pressure system to compete with high pressure single fluid systems for these applications. This paper presents work that demonstrates that the air-assisted DI system is capable of satisfying these extra demands, and outlines the potential benefits and indeed synergies between the application of air assisted direct fuel injection and intake charging of automotive gasoline engines.

This paper firstly summarizes the developments of the next generation air-assisted fuel injection system, incorporating the potential for variable fuel metering differential pressures for increased dynamic range. Further more, a fuel supply system designed to minimize the fuel system parasitic associated with this system is proposed.

The part load combustion capability of a pressure charged engine fitted with the Orbital spray guided direct injection combustion system is also presented. Engine emissions and fuel consumption are shown across a range of load conditions, with particular focus on the effect of intake manifold pressure at higher part load operation.

AIR-ASSISTED DIRECT FUEL 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 favorable qualities of small fuel droplet size and low penetration rates during compression stroke injection [3]. 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 the combustion requirements, 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.

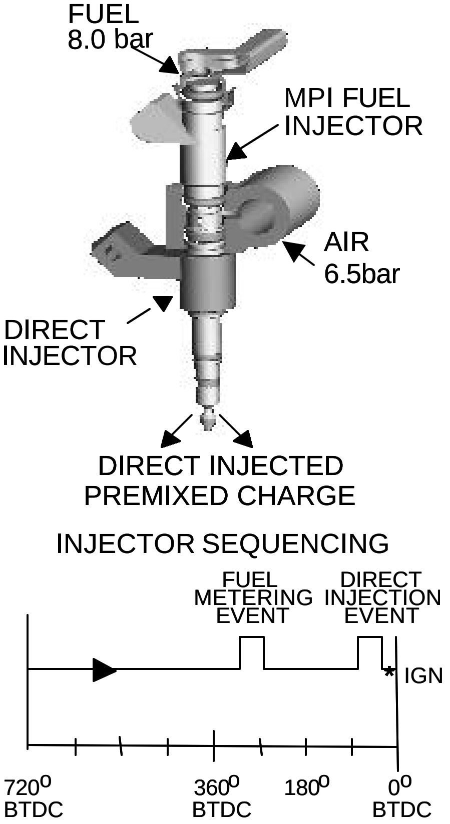


Figure 1. Air assisted fuel injection system components and operation schematic

As is illustrated in Figure 1, the fuel metering event can be located over a wide range, limited only by the total cycle duration of the engine. This provides a fuel metering turn down ratio with a constant pressure differential similar to current PFI engines. Future engines incorporating high levels of boost as well as reduced minimum fuel delivery requirements, results in the direct injected boosted engine requiring an increased fuel metering turn down ratio than is currently available for even fixed differential pressure PFI systems. Due to the relatively low fuel metering pressure of the air-assist injection system, it is possible to increase the fuel metering range by adopting a variable fuel metering differential pressure. There have been proposed many alternatives for achieving a varying fuel metering differential, with either air or fuel rail pressure variation, or a combination of the both. Two such schemes are illustrated below in Figure 2.

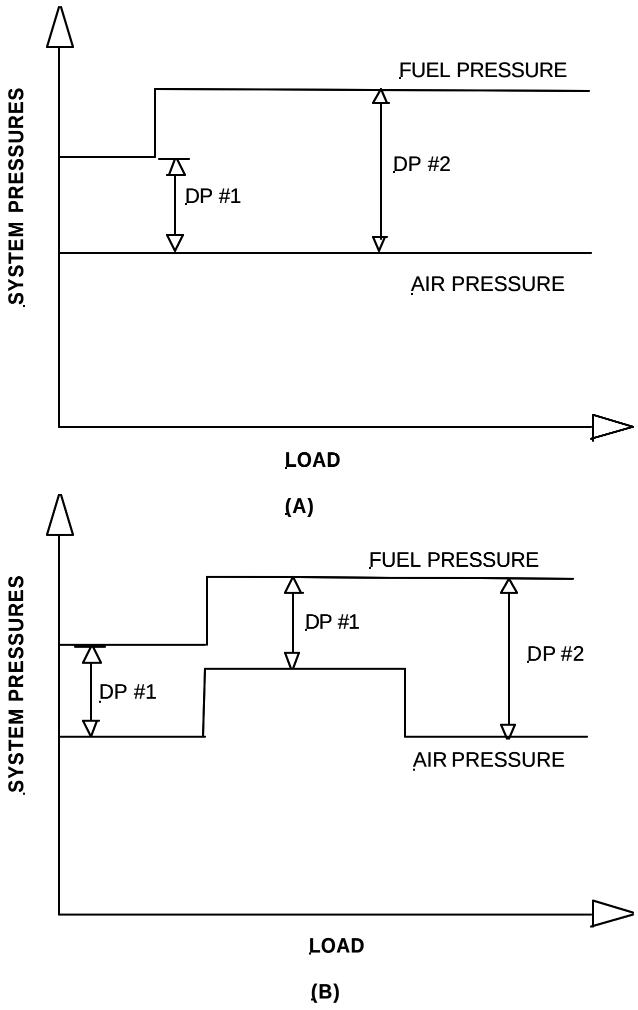


Figure 2. Air and fuel pressure schedules for increased fuel metering dynamic range

A system representative of those shown in Figure 2 has been chosen in order to demonstrate the effective fuel metering range that can be achieved with a system that operates with two fuel metering pressures.

Testing was performed with an air pressure of 6.5 bar and two fuel pressures, 7.5 bar and 9.0 bar, giving two fuel metering differential pressures of 1.0 and 2.5 bar. The fuel metering was performed on bench with a high impedance fuel injector, typical of that used on current production PFI engines. The minimum linear fuel pulse width was assumed to be 2.25 msec, while the maximum effective fuel metering duration was taken as 18.0 msec. This represents an 85% duty cycle of the fuel metering injector at 5500rpm engine speed.

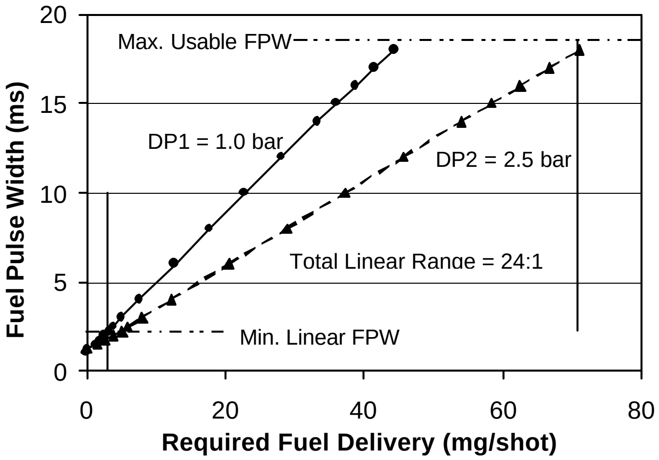


Figure 3. Fuel metering dynamic range testing

From Figure 3 it can be seen that for the system measured, a linear fuel metering dynamic range of 3 to 71 mg/shot was established, which equates to a turn down ratio of approximately 24:1. This high turn down ratio is achieved with relatively low fuel pressures, with the highest fuel pressure of the system being 9.0 bar.

In order to realize this increased dynamic range, some changes are required to the typical fuel system. One such fuel supply system has been proposed in order to deliver this type of varying fuel metering differential pressures. Figure 4 shows a schematic of such a system.

The system is described as a twin fuel supply system, operating with two distinct fuel pressures. The first pump is a high pressure, low flow device, similar to that already in series production on DI 2 stroke small motorcycle applications. The pump is coupled to a demand fuel regulator in tank with a target regulated fuel pressure of 7.5 bar gauge. The second pump is a high flow, high pressure pump. These pumps are similar in construction to current PFI fuel pumps, and are under development in order to supply to a higher pressure. This pump is coupled to a by-pass fuel regulator, with a nominal pressure of 9.0 bar gauge.

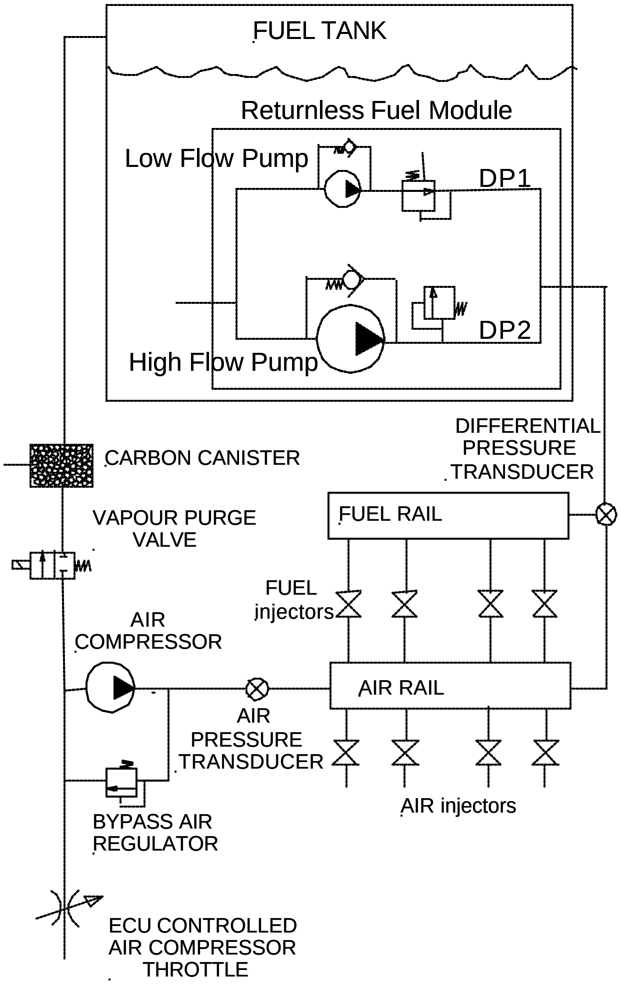


Figure 4. Schematic of twin fuel supply system

For low fuel flow demand (part engine load operation), only the first, low flow fuel pump would operate, producing a nominal fuel pressure of 7.5 bar, and therefore a nominal differential pressure (DP1) of 1.0 bar. When higher fuel flow is demanded (high engine load and speeds), the second pump is switched on via the engine control unit, and the fuel pressure is increased to 9.0 bar gauge, resulting in a fuel metering differential pressure (DP2) of 2.5 bar. Both fuel pumps and regulation devices are to be located in tank, resulting in a returnless fuel supply system from the tank.

The variable fuel pressure system relies upon a differential pressure transducer fitted between the fuel and air rails, in order to feedback the exact fuel metering differential pressure to the ECU for precise control of fuel metering. As suitable differential pressure transducers are now available, a system with fuel pressure not directly regulated relative to air injection pressure becomes feasible, which is what is proposed for these advanced systems.

The use of a twin fuel supply system offers additional benefits over and above that of increased fuel metering dynamic range. The low flow, high pressure fuel pump has a significantly lower power requirement than the high flow, high pressure pump. Figure 5 shows how the total parasitic load of the system can be reduced when using the low flow fuel pump. Also shown is the next evolution whereby the compressor is driven at half speed via the camshaft to further reduce the system parasitic load.

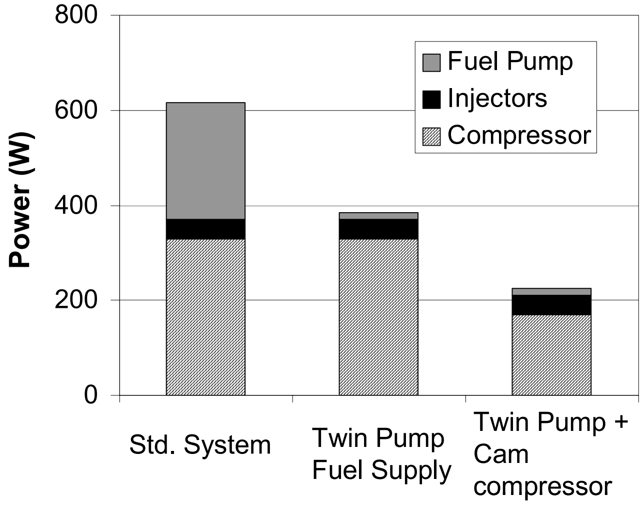


Figure 5. Air-assisted DI advanced system parasitic losses at 2000 rpm, 2 bar BMEP

The low flow pump typically has a displacement which can operate the engine over most part load operating conditions, leading to significant reductions in fuel consumption over typical driving cycles. Figure 6 shows fuel consumption comparison for the Orbital demonstrator vehicle with a 1360 ITWC fitted with a 2.0L engine, over the European drive cycle for the standard single fuel supply system compared to the twin fuel supply system proposed.

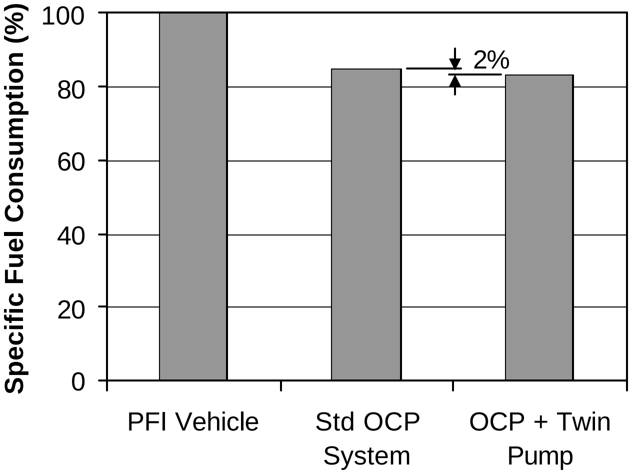


Figure 6. Vehicle fuel consumption reduction over NEDC with advanced fuel supply system

The reduced fuel supply parasitic equates to approximately a further 2% fuel consumption reduction in addition to the reduction already demonstrated in vehicle for the air-assist DI system with the more conventional fuel supply system.

The relatively large flow area of the air assist direct injector when compared to high pressure, single fluid injectors, enables rapid transfer of fuel into the combustion chamber at relatively low injection pressures. As the fuel metering is independent of the direct (or air) injector, this high flow area of the direct injector does not affect the ability to inject small quantities of fuel with very high metering accuracy. The air-assisted direct injector facilitates high speed engine operation as it is a high flow device and can deliver large quantities of fuel in very short durations. Since the injection duration is almost independent of the delivered quantity of fuel, this does not mean that the injection durations at low loads become excessively small. Indeed, the injection durations at 2000 rpm, 2 bar IMEP can be in fact similar of even longer than the injection durations at maximum power conditions [4].

The ability to transport fuel rapidly into the combustion chamber is very important for operation where a large quantity of fuel is required to be delivered at high engine speed, as required for full load, boosted engine operation. Residence (or mixing) time in the cylinder is very important for high speed, full load operation in order to ensure high efficiency as well as minimal smoke levels. Figure 7 shows how the direct injector can deliver high quantities of fuel with short direct injection durations.

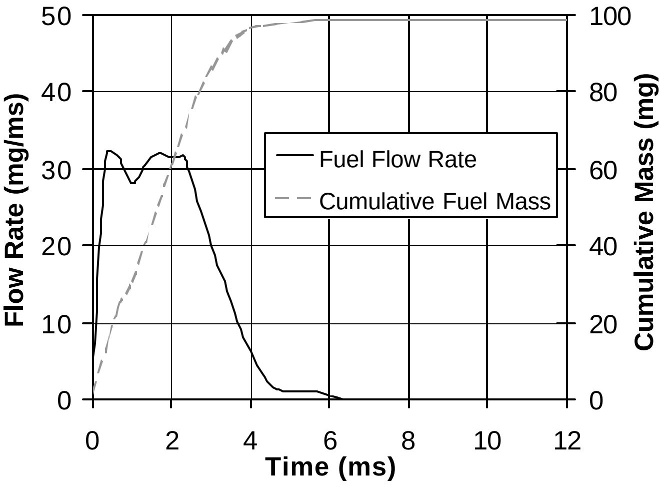


Figure 7. Instantaneous fuel flow rates during injection for 100 mg/injection event

DIRECT INJECTION SPRAY-GUIDED COMBUSTION SYSTEM

The combustion system can be described as an air-assisted, direct injection, spray guided system, with the direct injector centrally located in the combustion chamber, and injection direction close to parallel with the cylinder bore axis. The system utilizes close spacing of the direct injector and spark location; see Figure 8. A detailed description of the combustion system can be found in [3] and [5].

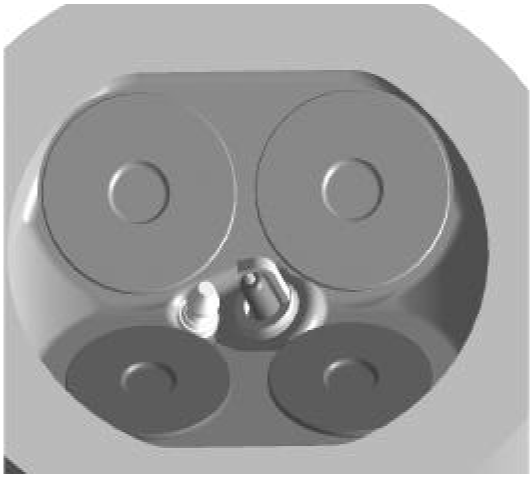


Figure 8. Combustion chamber design of air-assist, spray guided direct injection system.

For low load, stratified operation, the ignitable fuel mixture is created by injecting directly toward the spark location. This means that there is no secondary mechanism to transport the fuel from the injector to the spark location, for example deflection from wall details and/or transportation due to high in-cylinder gas motion. For this reason, there is no specific in-cylinder gas motion required, and in fact, low air motion has been shown to provide distinct benefits at low load, stratified operation [5].

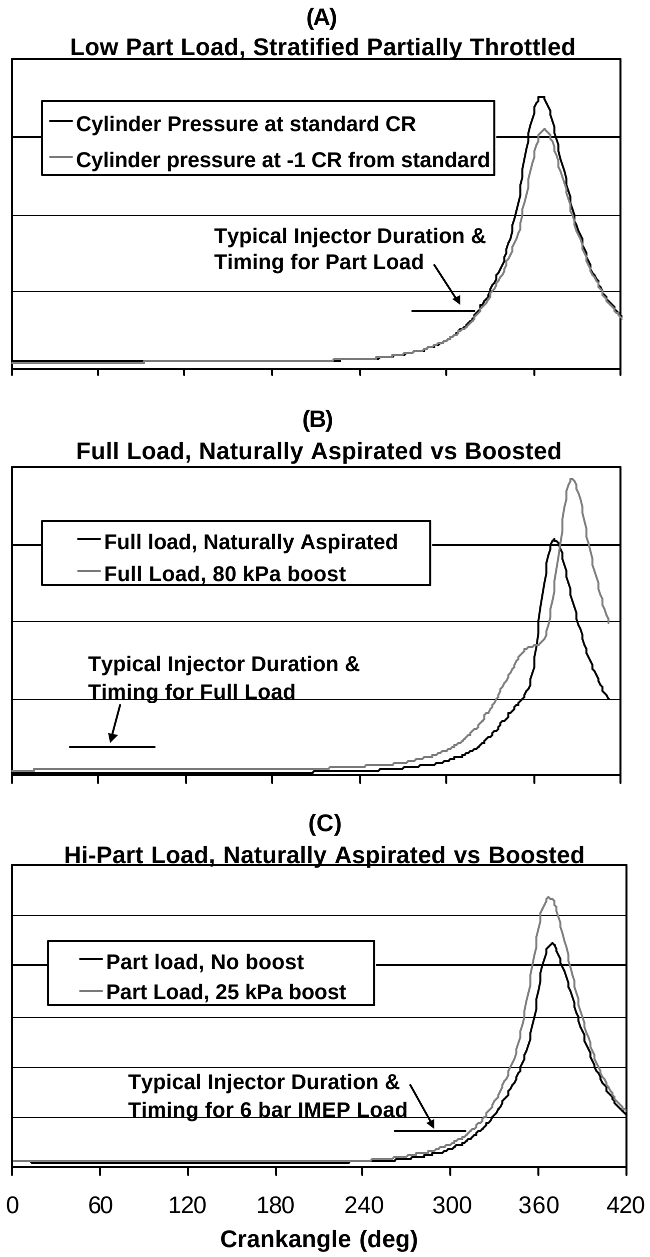
Though direct injection gasoline engines with combustion systems requiring in-cylinder charge motion initiated through the use of specific intake port design or inclusion of swirl valves can solicit the use of pressure charging to compensate for the disadvantages in volumetric efficiency [6], a pressure charged DI engine incorporating the Orbital developed combustion system allows the use of inlet ports imparting low in-cylinder motion. The application of low tumble inlet ports facilitates less harsh combustion, see [7], and a reduced demand on boost to achieve high airflow through the inlet port. Improved full load performance for turbocharged engines incorporating air-assisted direct injection is a potential outcome through increased knock tolerance provided by in-cylinder charge cooling effect of direct injection.

COMBUSTION SYSTEM OPERATING REGIMES FOR INLET CHARGED ENGINES

The ability of the relatively low pressure air-assist injection system to operate successfully under boosted conditions has been questioned. For naturally aspirated four-stroke gasoline engines, the system has been demonstrated to have the ability to operate in a highly stratified mode at part load, significantly reducing fuel consumption [5]. For boosted engine operation however, the cylinder pressure increases compared to a naturally aspirated engine, and the question of the air-assist system's compatibility with engines designed to run boosted must be addressed.

In order to understand the demands on the combustion system for an engine that is designed to run boosted at full load operation, and lean-stratified operation at low loads, we can consider three distinct modes of operation which are illustrated in Figure 9:

1. **Low part load operation:** For lower part load operation where the inlet manifold pressure is less than atmospheric, the compression pressures are very similar to a naturally aspirated engine or potentially lower due to typically lower compression ratios used for boosted engines. This mode of operation would typically apply to loads of 5 bar IMEP or less.
2. **High load operation:** During high to full load operation, the inlet manifold pressure is boosted above atmospheric conditions. The cylinder pressure is increased throughout the cycle when compared to naturally aspirated engines. At these high load conditions, the engine is operated in a homogeneous combustion mode with early injection timings in the induction stroke. The cylinder pressure during the induction stroke is increased only by the level of boost, and therefore has little effect on the differential pressure between the direct injector and combustion chamber.
3. **Mid to high part load operation:** At higher part load operation, there may be the option of boosting the engine for increasing the lean operation region. When boosting the inlet during this mode of operation, the cylinder pressure during the intake and compression strokes is increased above that for naturally aspirated engines. This increase in the compression pressures potentially poses the greatest challenge for the air assisted injection system due to its relatively low injection pressures, and therefore is the focus of the engine testing results as presented in this paper.



(A) Low Part Load, Stratified Partially Throttled

(B) Full Load, Naturally Aspirated vs Boosted

(C) Hi-Part Load, Naturally Aspirated vs Boosted

Figure 9. Operating regimes of direct injected, pressure charged gasoline engine

PART LOAD OPERATION WITH BOOSTED INLET CONDITIONS

SINGLE CYLINDER ENGINE TESTING DESCRIPTION

In order to investigate the effect of boosted inlet manifold pressure on the mid to higher part load operation, a program of single cylinder research engine testing was undertaken. The basic engine specifications are listed below in Table 1. The combustion chamber geometry utilized was representative of typical 4-valve per cylinder pent roof combustion chambers incorporating the OCP spray guided combustion system. The air injection pressure used for the results presented was 7.5 bar gauge.

Displacement	450 cc
Compression Ratio	11.0:1
Inlet Port Configuration	Low tumble, No swirl
Valve Arrangement	4 Valve, DOHC
Direct Injector	Synerject part # 37x-113
Fuel Metering Injector	Siemens Deka II
Air Injection Pressure	7.5 bar gauge
Fuel Supply Pressure	9.0 bar gauge

Table 1. Single Cylinder Engine Specifications

The pressure charged single cylinder testing was aimed at simulating turbocharged engine operation rather than externally driven supercharged operation, as turbocharging is believed to be the simplest of the two pressure charging methods to offer the potential to achieve improvements in the overall thermal efficiency and control the engine out emissions. The emissions control was believed to be a particularly important differentiation between charging methods, as external EGR to control NOx emissions becomes difficult to achieve with mechanical supercharges. To simulate turbocharged operation, the engine was operated with a positive displacement blower independently driven to supply the engines inlet manifold with charge air under pressure. The air delivered to the inlet manifold was temperature and pressure controlled. The exhaust pressure was controlled via a throttle located in the exhaust system, with a schedule to replicate the exhaust pressure of a modern 4 cylinder turbocharged gasoline engine for the inlet manifold pressures under test. As this was a preliminary study only, valve timings were not changed from naturally aspirated to boosted engine operation.

To characterize the operation at the mid to high part load regime, an engine speed of 2000 rpm was selected and a series of engine load points investigated with four levels of inlet manifold pressure, these being naturally aspirated (less than or equal to atmospheric pressure) and 5, 15 and 25 kPa boost. At each combination of load and inlet pressure, the ignition timing, injection timings and EGR levels were always optimized. To be able to compare results directly, it is important to minimize the number of variables, such that as much as possible, any improvements identified are clear, and without compromise. To achieve this, a minimum acceptable combustion stability was maintained for all test results and a maximum engine out NOx emissions level was also defined for each load condition. Table 2 lists the constraints applied to all data recorded unless otherwise shown

Load in IMEP (Bar)	COV of IMEP (%)	ISNOx (g/kWh)
4	3.75	2.0
6	3.3	3.0
8	2.5	4.0

Table 2. Stability & Oxides of Nitrogen (NOx) constraints

NOx emissions were chosen as a constraint when operating at lean conditions, as these emissions are the most challenging to reduce with current after-treatment technologies. With a Lean NOx storage and release catalyst system, NOx accumulated during lean operation must be purged by relatively rich operation of the engine, resulting in increased fuel consumption. In the absence of any correction factors, it is therefore necessary to maintain the same engine out NOx emissions when making a quantitative comparison of fuel consumption.

ENGINE RESULTS

2000 RPM, 8 bar IMEP

Figure 10 shows indicated specific fuel consumption and emissions at 2000 rpm, 8 bar IMEP for each level of inlet manifold pressure. At this high part load condition, the specific fuel consumption is reduced as the inlet manifold pressure is increased. A reduction in fuel consumption of approximately 8% was achieved at the highest boost condition when compared to homogeneous, stoichiometric operation with EGR.

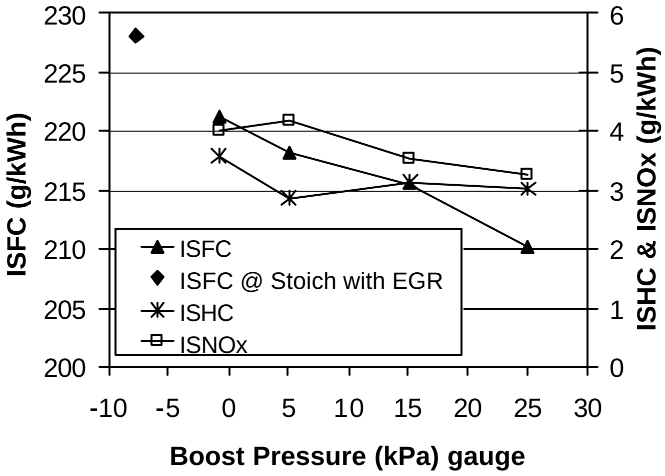


Figure 10. Fuel Consumption & Emissions at 2000rpm, 8.0 bar IMEP for boosted inlet conditions

The hydrocarbon (HC) emissions were found to be relatively insensitive to inlet manifold pressure at 8 bar IMEP, with nearly a constant level of approximately 3 g/kWh being achieved for all but the lowest manifold pressure tested. This represents very good control over engine out HC emissions even as the overall dilution ratio is increased. The Oxides of Nitrogen (NOx) emissions conformed to the criteria set for this speed and load point, being less than 4.0 g/kWh for all boost levels.

Investigating the cause for the fuel consumption reduction as inlet manifold pressure is increased, the gross indicated specific fuel consumption (G.ISFC) and gas exchange pumping work were considered as shown in Figure 11.

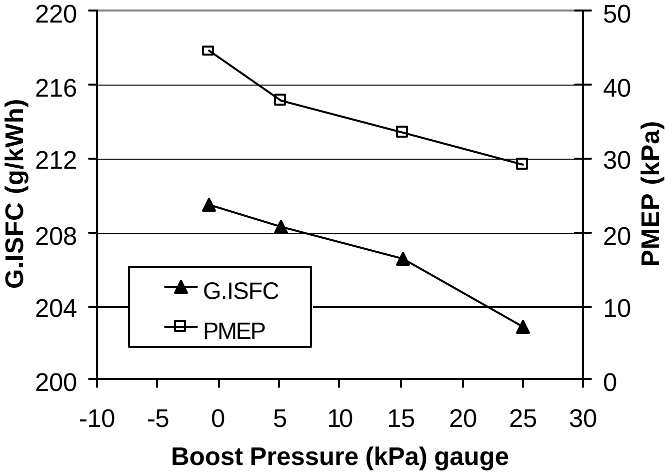


Figure 11. Gross indicated specific fuel consumption and pumping work at 2000 rpm, 8 bar IMEP

Both the gross indicated specific fuel consumption and pumping work reduced as the inlet pressure was increased, thereby both contributing to the indicated specific fuel consumption reduction as shown in

Figure 10. The reduction in pumping is work is due to the higher inlet manifold pressure above atmospheric pressure actually forcing the piston during the intake stroke. At this engine speed, the positive piston forcing effect more than compensates for the increase in exhaust stroke pumping work due to the higher exhaust pressures associated with turbocharging. The increase in gross indicated thermal efficiency (as represented by the reduction in gross indicated specific fuel consumption) is thought to be due to dilution effects. The higher dilution of the fuel at the higher manifold pressures increases the ratio of specific heats of the mixture, increasing the thermal efficiency of the combustion process [8]. The higher dilution also leads to lower bulk gas temperatures, reducing heat transfer to walls, and further increasing the thermal efficiency.

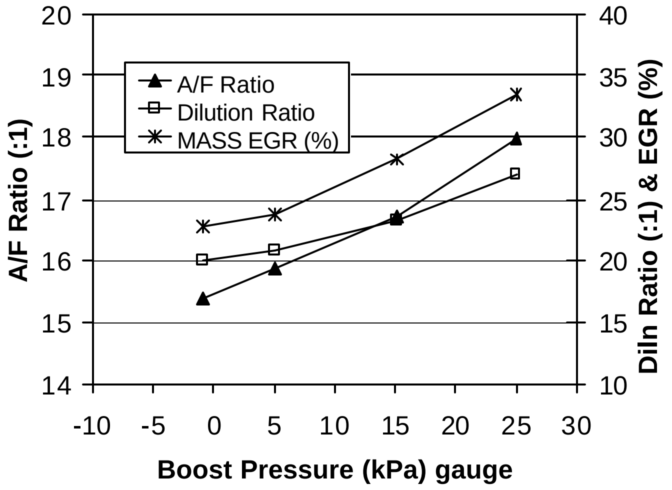


Figure 12. Air/fuel ratio, dilution (gas/fuel) ratio and EGR mass at 2000 rpm, 8 bar IMEP

The air/fuel ratio, EGR rate and intake gas (air and EGR) dilution ratio are shown in Figure 12. For constant load condition, increasing inlet manifold pressure naturally must increase the overall dilution ratio of the fuel. The split of increased dilution with either intake air or recirculated EGR, however, can be manipulated. As the boost level was increased, the air/fuel ratio increased from approximately 15.4:1 up to 18:1 at 25 kPa boost. In order to maintain the NOx emissions constraint, the EGR mass was increased in parallel to increased airflow. At the highest boost levels tested at the 2000 rpm, 8 bar IMEP condition, over 30% of the inlet charge was EGR. These high levels of EGR would not be normally feasible with naturally aspirated operation at these engine loads.

Figure 13 shows the combustion stability (expressed as the co-efficient of variation of IMEP) and the smoke levels versus inlet manifold boost. The combustion stability is shown to be within the constraints as defined in Table 2. The smoke levels, measured via a filter smoke number, remain relatively constant showing little sensitivity to the boost levels tested. The majority of conditions show a level of approximately 0.3 FSN. The smoke level measured was found to be more sensitive to injection timings and not boost pressure, explaining the lack of any trends evident in Figure 13. The use of boosted inlet conditions has been shown to be an effective means to control the smoke level for single fluid direct injection combustion systems when operating stratified at higher load conditions [9]. For the air-assisted spray guided system, this advantage is not obvious. As the injection and combustion system allows the injection timing to be tailored to the combustion event requirements, low smoke emissions can be achieved at high part load operation without inlet charging.

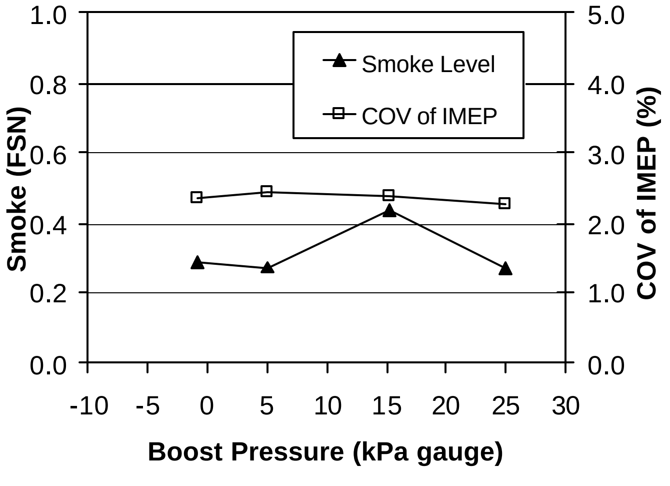


Figure 13. Combustion stability and smoke level at 2000 rpm, 8 bar IMEP

LOAD SCAN

Investigating the effect of inlet manifold boost at other part load operation, Figure 14 shows the fuel consumption comparison for three different loads at 2000 rpm. As the boost pressure was increased, some reduction in fuel consumption was evident for all three loads presented. However, the reductions at 4 bar IMEP and 6 bar IMEP were limited, with the major reduction occurring at low increases in manifold pressure compared to the non-boosted inlet condition. There was found to be negligible further reductions in fuel consumption as the boost level was increased beyond 5 kPa. This is different to the effects seen at 8bar IMEP, where continued fuel consumption reduction occurred as the boost level increased.

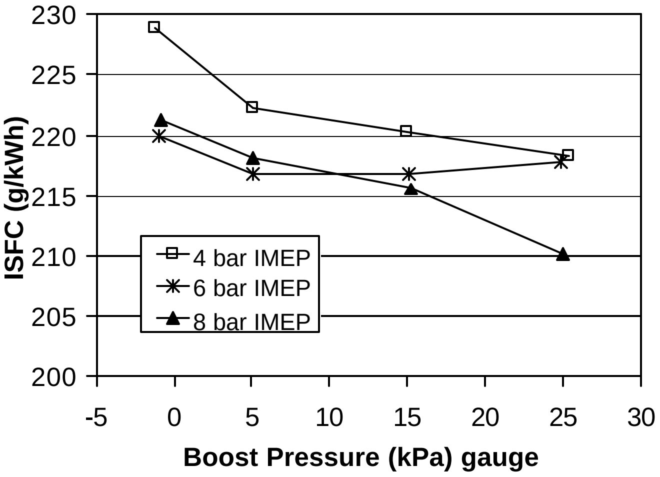


Figure 14. Indicated specific fuel consumption at different inlet boost levels

As boost pressure increased, the gross indicated specific fuel consumption remained relatively constant for the 4 and 6 bar indicated loads, with slight increases at the highest boost levels (see Figure 15). This is significantly different from the result at 8 bar IMEP (Figure 11) where the G.ISFC continued to reduce as inlet manifold pressure increased. The increase in G.ISFC for these lower loads offsets the further reduction in pumping work that occurred as the boost pressure was increased. The result of these effects is that the fuel consumption reduction enabled by boosted conditions at the NOx emissions constraints applied according to Table 2 is limited with boost at loads less than 6 bar IMEP. Further studies, however, as shown in the next section may indicate that boost is an effective means of reducing the engine-out NOx emissions levels without increasing fuel consumption at these part load points, as the boost enables a greater mass of EGR to be used without reducing the air/fuel ratio to an extent where it causes significant adverse affects on the thermal efficiency.

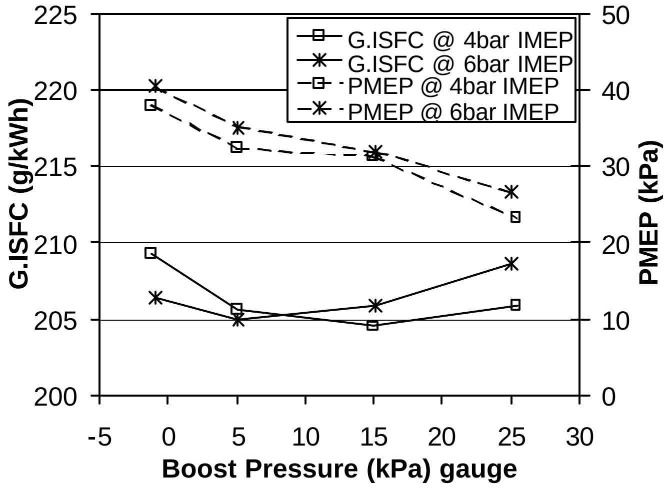


Figure 15. Gross indicated specific fuel consumption and pumping work at 2000 rpm, 4 and 6 bar IMEP

When compared to 8 bar IMEP, the 4 and 6 bar IMEP loads were already running significantly lean A/F ratios with atmospheric inlet conditions, as shown in Figure 16. As the contribution of specific heat effects to improved thermodynamic efficiency is most significant as air/fuel ratio is increased from near stoichiometric operation, the benefits due to this are small at 4 and 6 bar IMEP as the manifold pressure is increased above atmospheric.

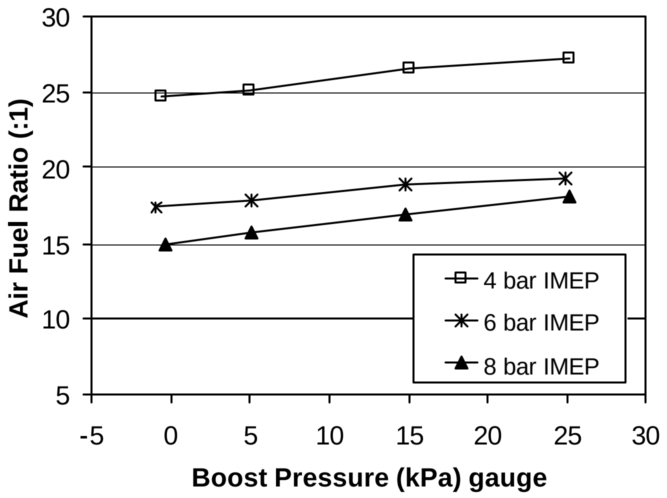


Figure 16. Inlet Air to Fuel Ratio for Boosted Inlet Conditions

The reason for increased fuel consumption is largely due to non-optimum combustion. Figure 17 shows that as the boost pressure was increased at 2000 rpm, 4 bar IMEP, the burn duration was increased, and the location of 50% mass fraction burned became more advanced. These effects contribute to the increase in G.ISFC, limiting further reductions in N.ISFC at these lower load conditions with increased boost pressures.

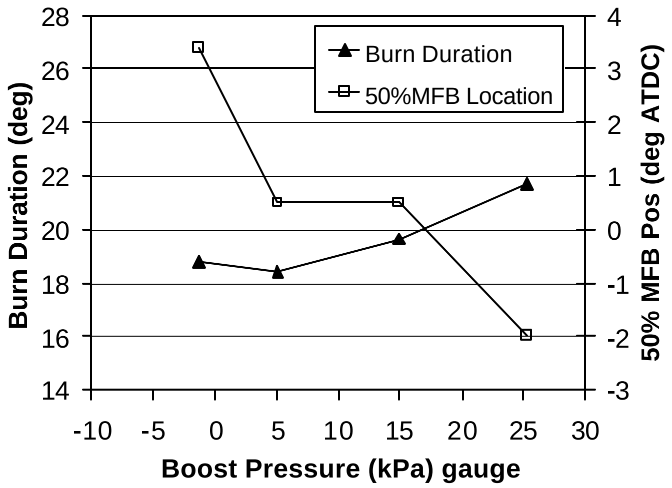


Figure 17. Combustion duration and location of 50% mass fraction burned at 2000 rpm, 4 bar IMEP

NOX EMISSIONS SCANS

NOx emissions scans were conducted on the single cylinder research engine at each boost level at 2000 rpm, 8 bar IMEP. The previous data indicated that at a constant NOx emissions level, the highest boost pressure offered the greatest fuel consumption reduction at this load condition. In order to minimize the post treatment burden, it is beneficial to reduce the engine out NOx emissions as much as possible, especially if this can be achieved with minimum compromise in fuel consumption.

The effect of engine out NOx reduction on the fuel consumption through increasing EGR levels is shown in Figure 18. A general trend of increasing fuel consumption with lower NOx emissions levels is apparent. The lower NOx emissions were achieved by increasing the level of external EGR while maintaining the same manifold pressure. The increased EGR level displaces intake air, leading to richer A/F ratios run in cylinder. The amount of EGR added was limited to that required to achieve a near stoichiometric A/F ratio, as it was not considered meaningful to operate the engine richer than a stoichiometric mixture at part load conditions. At stoichiometric conditions, traditional three-way catalyst aftertreatment systems have very high NOx conversion efficiencies, so reducing the engine out NOx becomes less important when compared to lean operation.

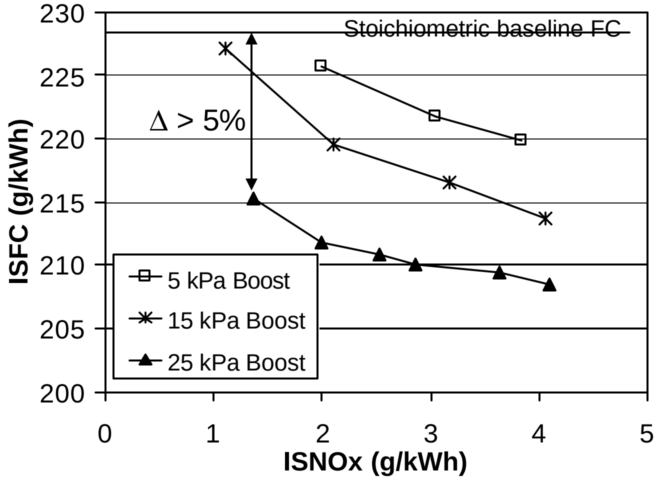


Figure 18. Fuel consumption for reduced NOx emissions at 2000 rpm, 8 bar IMEP

The increasing fuel consumption trend for the 25 kPa boost data is not as pronounced as for the other manifold pressures, raising a potentially useful characteristic that could be exploited. Figure 18 shows that a ISNOx loading of around 1.5 g/kWh is possible to achieve with a ISFC of close to 215 g/kWh, representing a fuel consumption reduction of over 5% when compared to homogeneous, stoichiometric operation with EGR. For a 2.0 liter displacement engine, 2000 rpm, 8 bar IMEP represents 26.7 kW net indicated power. Assuming an aged LNC with 1 gram NOx storage and a 90% storage efficiency, the engine could be run for approximately 80 seconds before invoking any combustion mode change to regenerate the catalyst. Assuming that a 3 second period of near stoichiometric combustion mode operation is required to purge 1 gram of NOx, and 80 seconds is required to fill the LNC at steady state operation, the purge time share equates to approximately 3.5% at this speed and load condition. This small period of NOx catalyst purging requirement facilitates near to the full benefit of reduced fuel consumption with boosted lean operation to be realized in a vehicle application.

Figure 19 shows the air fuel ratio and the mass EGR for each inlet manifold pressure as a function of engine-out NOx emissions levels. As the NOx emissions were reduced, the air/fuel ratio was reduced, with the corresponding increased levels of EGR. The higher boost levels resulted in the ability to maintain air/fuel ratios significantly above stoichiometric as the EGR level increased.

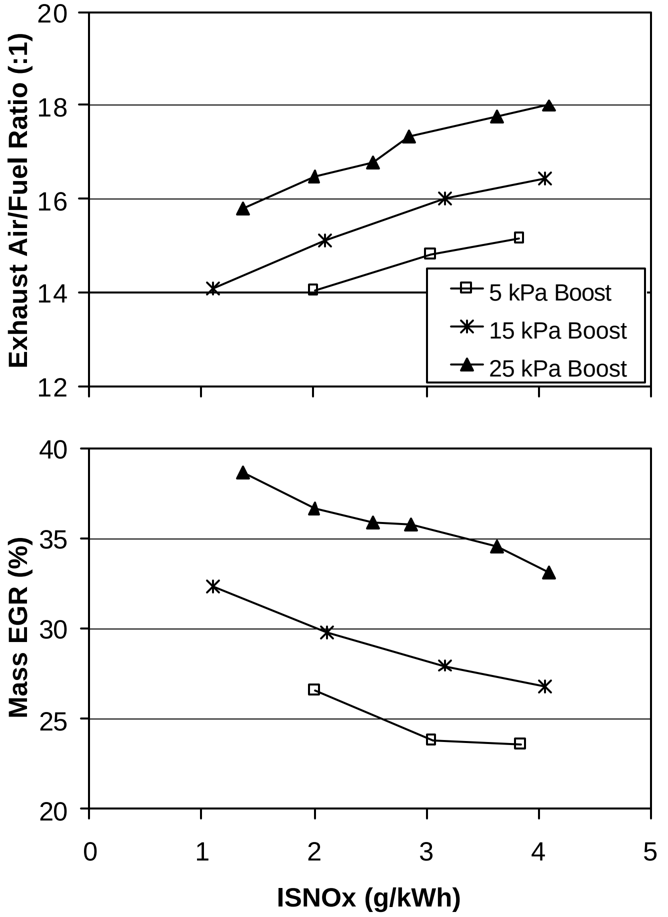


Figure 19. Air/fuel ratio and EGR rate for reduced NOx emissions at 2000 rpm, 8 bar IMEP

At the low boost levels, it is evident that the air/fuel ratio passes through stoichiometric level much earlier as the EGR level was increased. These higher boost pressures therefore enable the ability to achieve the significant fuel consumption reductions over the homogeneous, stoichiometric baseline, as the NOx emissions are reduced.

The smoke characteristic is shown in Figure 20. An acceptable smoke level of below 0.3 FSN was maintained for all manifold pressures and A/F ratios tested. The air-assisted spray guided direct injection combustion system is not subject to increasing smoke levels with reducing A/F ratio and increasing EGR levels encountered when calibrating the combustion system to achieve low engine-out NOx emissions.

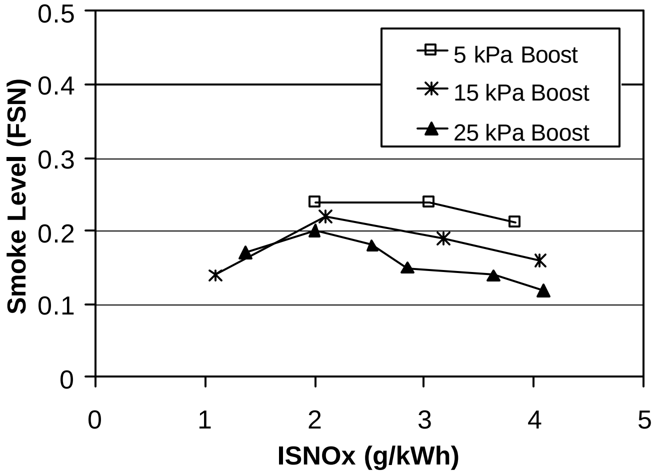


Figure 20. Smoke levels for reduced NOx emissions at 2000 rpm, 8 bar IMEP

Figure 21 shows the hydrocarbon emissions level as a function of NOx emissions at 2000 rpm, 8 bar IMEP. The results show that there is only a very slight trend of increased HC emissions as the NOx emissions level is reduced, with the absolute levels remaining very competitive with homogeneous PFI combustion systems.

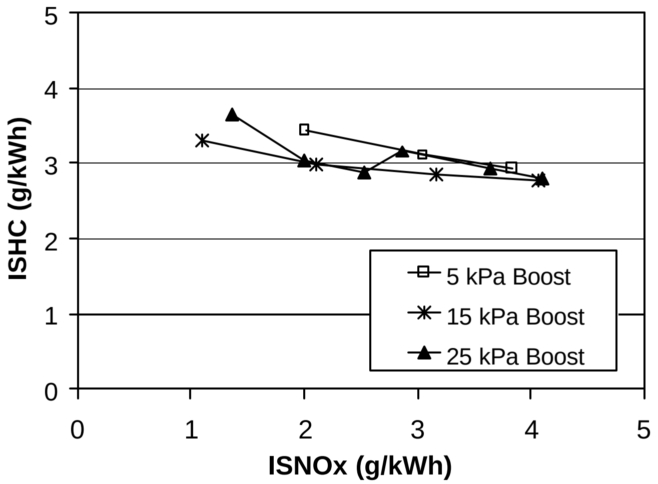


Figure 21. Hydrocarbon emission levels for reduced NOx emissions at 2000 rpm, 8 bar IMEP

SUMMARY / CONCLUSIONS

The air-assisted, spray guided direct injection combustion system has been demonstrated to have the capability to meet the challenges associated with application on pressure charged engines.

The fuel injection system, with the decoupling of fuel metering from the direct injection event, coupled with a two-stage metering differential pressure is able to deliver a linear fuel metering dynamic range with a turn down ratio of greater than 24 to 1. A new method of supplying fuel to the injection system in order to achieve the variable fuel differential pressures has also been presented which provides a low cost means of achieving the two metering differential pressures as well as the potential to significantly reduce the fuel supply system parasitic. Further reductions in fuel consumption of approximately 2% have been predicted for medium sized passenger vehicles over typical drive cycles as a result of the reduced fuel pump parasitic offered by this system.

The spray guided combustion system responds positively to an increased dilution level through boosting the inlet manifold at higher part load. Fuel consumption reduction of approximately 8% compared with stoichiometric operation has been achieved by operating with higher inlet manifold pressures, while still maintaining acceptable emissions levels (including smoke) and combustion stability. This reduction in fuel consumption is due to both increased gross indicated thermal efficiency and reduced gas exchange pumping losses, even with the increased exhaust pressure associated with turbocharging.

Investigating the effects of reducing engine out NOx emissions at higher part load operation, it was possible, with significant inlet manifold boosting, to achieve engine out NOx emissions as low as 1.5 g/kWh in combination with greater than 5% reduction in fuel consumption. The combination of low engine-out NOx emissions and fuel consumption reduction is important in order to realize the potential fuel savings associated with running lean in a vehicle application. This is due to allowing extensive lean operation periods between lean NOx storage catalyst regeneration intervals, thereby minimizing the fuel consumption penalty of the NOx regeneration cycles. The application of air-assisted, spray guided direct injection to the downsized turbocharged gasoline engine has therefore the potential to further reduce real world fuel consumption, especially in markets such as Europe where high speed driving, equating to high part load operation, is common. This potential is important in order to deliver direct tangible benefits of direct fuel injection technology to the consumer.

ACKNOWLEDGMENTS

The authors would like to thank all the dedicated personnel at Orbital Engine Company who have either directly or indirectly contributed to this paper.

REFERENCES

1. Brogan, M.S., Swallow, D., Brisley, R.J., Worth, D., Yang, K.C., “A New Approach to Meeting Future European Emissions Standards with the Orbital Direct Injection Gasoline Engine,” SAE 2000-01-2913

2. Smyth, J.G., Indra, F., Sczomak, D.P., “Zentraleinspritzung - die Zukunft der Direkteinspritzung?: *Central Injection - the Heart of the Next Generation DI-Gasoline Engine?*,” Aachen Colloquium, 2001.
3. Houston, R., Cathcart, G., “Combustion and Emissions Characteristics of Orbital’s Combustion Process Applied to Multi-Cylinder Automotive Direct Injected 4-Stroke Engines,” SAE 980153.
4. Cathcart, G., Railton, D., “Improving the Robustness of Spray Guided DI Combustion Systems: The Air-Assisted Approach,” JSAE 20015360.
5. Cathcart, G., Zavier, C., “Fundamental Characteristics of an Air-Assisted Direct Injection Combustion System as Applied to 4 Stroke Automotive Gasoline Engines,” SAE 2000-01-0256.
6. Kramer, F., Schwarz, Ch., Witt, A., “Effect of Compression Ratio on the Combustion of a Pressure Charged Gasoline Direct Injection Engine,” SAE 2000-01-0250.
7. Olofsson, E., Alvestig, P., Bergsten, L., Ekenberg, M., Gawell, A., Larsén, A., Reinmann R., “A High Dilution Stoichiometric Combustion Concept Using a Wide Variable Spark Gap and In-Cylinder Air Injection in Order to Meet Future CO2 Requirements and World Wide Emissions Regulations,” SAE 2001-01-0246.
8. Scussel, A.J., Simko, A.O., Wade, W.R., “The Ford PROCO Engine Update,” SAE 780807.
9. Wirth, M., Mayerhofer, U., Piock, W.F., Fraidl, G.K., “Turbocharging the DI Gasoline Engine,”SAE 2000-01-0251.

CONTACT

For more information, please contact the Orbital Engine Company website; www.orbeng.com