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The Application of Air-Assist Direct Injection for Spark-ignited Heavy Fuel 2-Stroke and 4-Stroke Engines

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There is a growing requirement for lightweight high performance engines capable of operation with heavy fuels such as JP5 (F44), JP8 (F34) and diesel fuels as well as maintaining the capability of running on unleaded gasoline. Traditionally heavy fuels are associated with operation in compression ignition engines which exhibit poor power to weight characteristics. Today's engine applications call for much greater mobility and flexibility in use, especially in applications such as outboard engines, motorcycles, All Terrain Vehicles, Light Aircraft and portable generator sets. Compression ignition engines with their poor power to weight and vibration characteristics are less likely to succeed in these applications. These requirements are more likely to be met by the development of a spark ignition engine capable of operating on these heavy fuels.

With the development of Direct Injection technologies it is now possible to achieve sufficient control over the combustion process in spark ignition engines to overcome the poor physical properties of the heavy fuels that to date have prevented good combustion being achieved across the entire speed and load domain of the engine.

This paper explores the development path and results from several conversions of direct injected gasoline engines, both 2 and 4-stroke, to operate as spark ignition heavy fuel engines, thus offering the fuel of choice whilst retaining the weight advantages and the desirable power to weight ratios of the gasoline engines.

Keywords: Combustion, Kerosene, Diesel, 2-Stroke Engine, 4-Stroke Engine, Spark Ignition

1. INTRODUCTION

Through out the history of the engine, there has been a clear divide between the spark ignition (Otto-cycle) gasoline engine and the compression ignition (Diesel-cycle) engine using the heavier fuels such as diesel. With the advent of today's electronic control, combustion and fuel system developments, there is growing interest in combining the positive attributes of both the spark ignition and compression ignition engines. This has been led initially by the desire of the military to have one fuel type to cover all vehicles and equipment in their theater of operation (i.e. 'one fuel policy') which includes safety and ease of operations considerations. Following from the military requirements, there is also an increasing demand for heavy fuel high mobility engines in non military applications, in the service and support industries including emergency services, oil field support services and other commercial applications where safety is a key consideration and/or diesel or kerosene is the more available and affordable fuel.

The typical compression ignition engine has been the only practical option for heavy fuel applications to date, however has significant drawbacks, especially in an environment demanding high mobility such as auxiliary power sources, outboard engines, generators and UAV's (Unmanned Aeronautical Vehicles). These drawbacks include:

- Poor power to weight ratio
- Poor cold start capability
- Poor noise, vibration and harshness ('NVH') characteristics
- Inability to run with the lighter fraction fuels such as gasoline

Previous developments of spark ignition heavy and multi-fuel engines were limited with spark plug fouling/carbonning, the inability to be able to run satisfactorily across the total load/speed range and poor startability, a problem exacerbated with cold environmental conditions.

The advent of modern electronic control and advanced combustion and fuel system development has enabled spark ignition engines to service the heavy fuel and mobile engine application market. This has come about primarily due to enhanced fuel mixture preparation and fuel/air charge containment, both critical aspects of operating spark ignition engines on both heavy and multi-fuels. The spark ignition heavy fuel engines can retain the desirable features of the gasoline engine in terms of power/weight and packaging size, and operate on a wider range of fuels that the traditional compression ignition engine.

The Air Assist Direct Injection systems, which have now been in commercial use in motorcycles, outboards, personal water craft (PWC) since the mid 1990’s, has particular attributes, as listed below, that are conducive for the spark ignition operation of heavy fuels:

- Low penetration
- Very small droplet size, typically approximately 5 micron Sauter Mean Diameter (SMD)
- Oxygen enrichment around the fuel droplets assisting the combustion initiation
- Ability to control the air/fuel ratio profile of the injected fuel and air charge

Multi-fuel 2-stroke outboards using the ADI systems have been recently introduced to the market [1,2]. These products are capable of operation on the specified heavy fuel and on gasoline, with the operator able to select the fuel choice. Following from these initial product developments, further applications have been instigated, including initial application to 4-stoke engines.

This paper examines the development of both 2 and 4-stroke spark ignition engines using an Air Assisted Direct Injection system and presents the capability of both 2 and 4-stroke engines converted to operate on multi fuels.

2. AIR-ASSIST DIRECT INJECTION COMBUSTION SYSTEM DESCRIPTION

Air Assist Direct Injection has been commercially applied to a range of 2-stroke engines, from 50 to 500 cc/cylinder displacements, and developmentally on 4-stroke engines, ranging from small motorcycle engines through to multi-cylinder automotive applications.

The combustion system developed by Orbital used on these applications can be best described as an air-assisted direct injection fuel system coupled with a spray guided combustion system.

2.1 AIR-ASSIST FUEL SYSTEM

The air-assist direct fuel injection system consists of the following major components as shown in Fig.1.

Fuel Metering (PFI) injector. A conventional port fuel injector is used to meter fuel into an interface region between the metering injector and the direct injector.

Air/Fuel Interface. An interface region exists to ensure correct fuel delivery from the metering injector into the direct injector. The interface also provides the link to the compressed air circuit that is used to force the metered fuel from the direct injector into the combustion chamber.

Direct (air) injector. This injector is best described as a charge injector, as it injects a mixture of fuel and air directly into the combustion chamber.

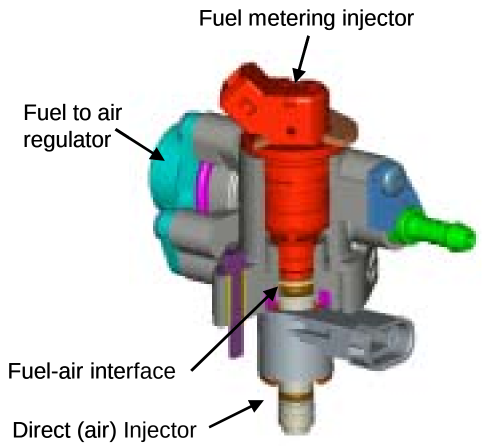


Fig.1 2-stroke 50cc motorcycle production fuel rail assembly

The operation of the fuel system is shown schematically in Fig.2. The fuel metering injector is pulsed to accurately meter a defined quantity of fuel into the interface region. The direct injector is then operated, resulting in a mixture of fuel and air to be simultaneously injected into the combustion chamber. This sequence separates the fuel metering from the direct injection event, which enables similar fuel metering turn down ratios to port fuel injection systems to be achieved using a constant pressure differential.

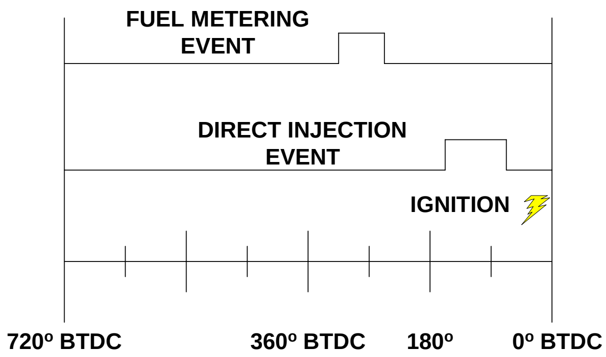
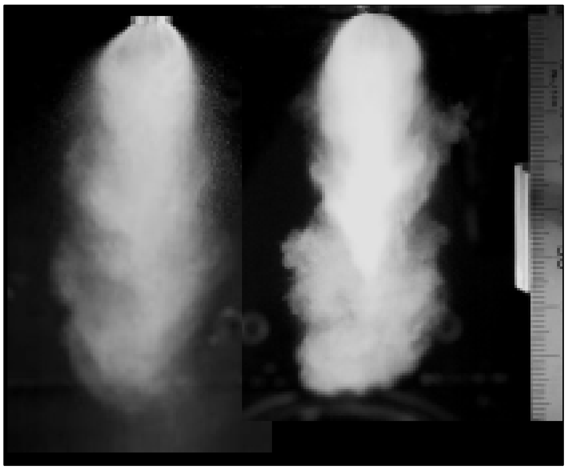


Fig.2 Schematic of typical injection sequence for air-assist DI fuel system

The air-assist injection system requires a supply of pressurized air and fuel. The typical air rail pressure of the system is between 500 to 650kPa (gauge). The fuel pressure is usually controlled via a pressure regulator with a reference relative to the air pressure (maintaining a constant metering pressure differential, typically between 100kPa to 250kPa). More details about the air-assist DI fuel system can be found in references [3] to [5].

The air-assisted direct injector has been shown to be a very efficient fuel atomizer [3]. Through the use of an air shear mechanism as the air is expanded (accelerated) through the nozzle, the fuel droplets leaving the injector are broken-up to provide an extremely well atomized spray. The ultra-small droplet sizes aid fuel vaporization which is especially important in heavy fuel applications, where the fuel is less volatile. Rapid evaporation of the fuel is extremely important to prevent spark plug fouling and cold start issues. The ability of the injector to efficiently atomize different fuel types, as well as maintaining similar spray characteristics, is important for having a true multi-fuel capable engine. Fig. 3 shows the small droplet size and spray shapes enabled by the air-assist direct injector for both diesel and gasoline type fuels.



DIESEL FUEL	GASOLINE FUEL
10 mg/shot	10 mg/shot
6.8 micron S.M.D.	5.72 micron S.M.D.

Fig. 3 Spray shape and droplet size comparison with diesel and gasoline

By having separate metering and direct injection control, it is possible to vary the duration and timing of the injection event, hence allowing greater control of the air-fuel mixture in the combustion chamber. Having this control enables the residence time of the fuel in the combustion chamber to be controlled. Increasing the residence time in the chamber promotes mixture preparation, better air utilization and lower smoke and soot formation issues, while reducing the residence time helps to control pre-ignition and engine knocking. The control enabled by the air-assist direct injection system allows a compromise to be achieved between these effects at all operating conditions of the engine.

2.2 COMBUSTION SYSTEM

The combustion system can be broadly described as an air-assist, direct injection, spray guided system, with the direct injector located as near to the center of the combustion chamber as possible, and the injection direction close to parallel with the cylinder bore axis. The system utilizes close spacing of the direct injector and spark location in order to promote true spray guided combustion, that is, an ignitable fuel mixture is created by injecting directly toward the spark location. Therefore, at highly stratified operation, there is no secondary mechanism required in order to promote an ignitable fuel-air mixture to the spark plug. For the 4-stroke engine this means that there is no requirement for specific in-cylinder bulk gas motion and the inlet ports can therefore be designed for high flow efficiency [6].

Providing the required mixture strength at the spark directly from the injection process means that there is no requirement for special piston crown shapes in order to achieve stable ignition of the fuel. A shallow piston bowl is often desirable, however only to provide increased containment of the injected fuel charge. This increased containment can provide reduced hydrocarbon emissions, improved fuel economy [3] as well as reduced bore wetting for some applications.

Fig.4 shows some typical combustion chamber designs for a 2-stroke engine application. Fig.5 shows two typical combustion chamber designs for 2-valve and 4-valve per cylinder 4-stroke engines. The close spacing between the injector and spark plug is evident in all of these designs. The relationship between the injector and spark plug is similar for both the production 2-stroke motorcycle and marine applications, and in the prototype 4-stroke applications.

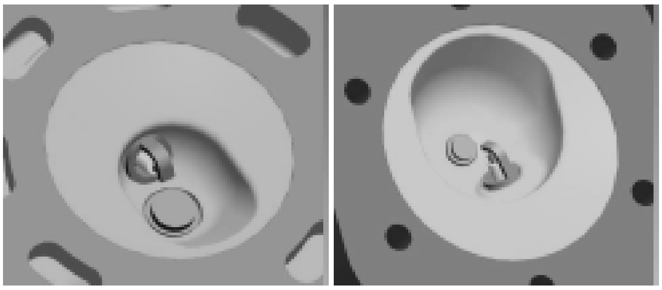


Fig.4 Typical 2-stroke combustion chamber configurations with air-assist, spray guided DI combustion system

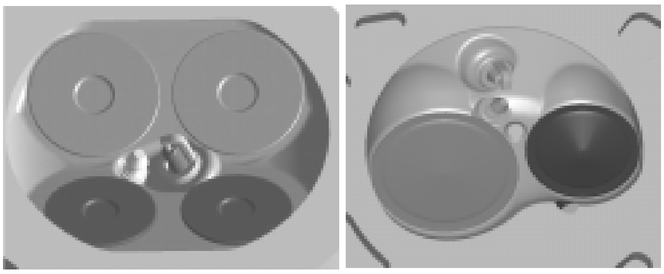


Fig.5 Typical 4-stroke combustion chamber configurations with air-assist, spray guided DI combustion system
(2 valve and 4 valve examples)

The key difference in the combustion systems on the 2 and 4-stroke engines is the location of the combustion chamber for charge containment. Whilst the spark plug injector relationship is common, the 2-stroke engine has the opportunity of having a designated combustion chamber volume contained in the cylinder head, with possibly a small bowl in the piston. The combustion chamber in the cylinder head can be designed to promote containment of the injected fuel. For the 4-stroke engine application, due to packaging constraints, the key charge containment design is incorporated in the piston.

3. PRACTICAL APPLICATION OF SPARK-IGNITED HEAVY FUEL ENGINES

Orbital Corporation has been involved in programs applying the air-assist DI system to 2-stroke and 4-stroke engine applications, primarily for gasoline, spark ignited applications. More recently, Orbital has been performing significant development of multi-fuel capable spark-ignition 2-stroke and 4-stroke engines using the same direct injection combustion system concept.

Orbital have applied the air-assist direct injection system to spark ignited heavy fuel engine applications ranging from small 50cc single cylinder 2-stroke engines, to larger multi-cylinder 3.0L V6 2-stroke engines (500cc/cylinder), as well as 4-stroke engines with cylinder sizes between 380 to 550cc. The fuels used for these applications include kerosene type fuels JP5 (F44), JP8 (F34), as well as diesel fuels (F76)

The systems today are designed to be able to operate in true multi-fuel formats, with the operator having the ability to select the fuel via a switch which engages the appropriate calibration to suit the specified fuel.

3.1 2-STROKE ENGINE APPLICATIONS

The combustion and calibration development of the spark ignition heavy fuel 2-stroke engine has been effectively carried out in 2 stages. The initial stage was focused on full load operation, as this was key in defining the combustion system design. Once this was established, the part load operation was developed to ensure satisfactory operation and optimized fuel economy across the total speed and load range.

Applications have been carried out over a range of products including outboard engines, UAV's and scooter engines.

(1) Full Load Operation

The key aspect to the optimization of the full load operation is in the control of pre-ignition and engine knock. With kerosene and diesel type fuels, the propensity to engine knock is greater. This is primarily due to the lower auto-ignition temperature of these fuels compared to gasoline. The kerosene and diesel fuels typically have relatively high Cetane numbers, which generally correspond to low Octane number (or knocking resistance) by definition. The engine performance is defined thus by the acceptable compression ratio and calibration at the speeds with the highest torque. The compression ratio is also determined by the selected range of fuels for the given application, with the diesel fuel typically showing the highest knock susceptibility, and thus limiting the compression ratio for the application. Running on kerosene or gasoline based fuels with this specification of compression ratio will results in a slight power loss compared to a compression ratio optimized for each fuel type.

Calibration techniques include the optimization of the fuel flux (the air to fuel ratio exiting the injector), the injection timing and duration and ignition timing. All of these parameters contribute to containment of the charge and minimizing the potential for knock to develop.

Development of knock sensing and knock control strategies can enable active optimization to be undertaken, allowing both enhanced power and to a degree, allowing operation without the operator having to select the specific fuel and corresponding calibration maps for that fuel.

Fig.6 shows the full load performance of typical 2-stroke engine applications with JP5 fuel. The full load performance is normalized against the baseline gasoline version of the engine. In some cases this is a direct injection baseline, and in others this is a carbureted or PFI engine.

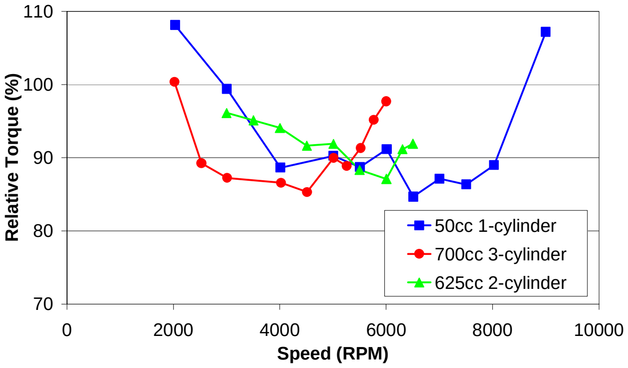


Fig.6 Full load performance comparison between carburetor and/or DI gasoline baseline and air-assist DI engine on JP5 for 2-stroke engines

The results show that some loss in full load performance occurs with JP5 compared to the baseline gasoline engine performance. The results show that at the lower and higher speeds, the torque loss is less than at the mid speeds. This is due to the higher propensity to knock at the higher BMEP levels encountered at the mid engine speeds. At higher engine speeds, not only is the BMEP reduced, but the high speed operation reduces the knock sensitivity.

A comparison is made at full load between JP5 and diesel fuel compared to the gasoline baseline engine in Fig.7 for a 700c, 3-cylinder 2-stroke engine. As can be seen, the loss in mid speed torque becomes greater with the diesel fuel when compared to the JP5 fuel. At the low and high engine speeds, similar full load torque is achieved.

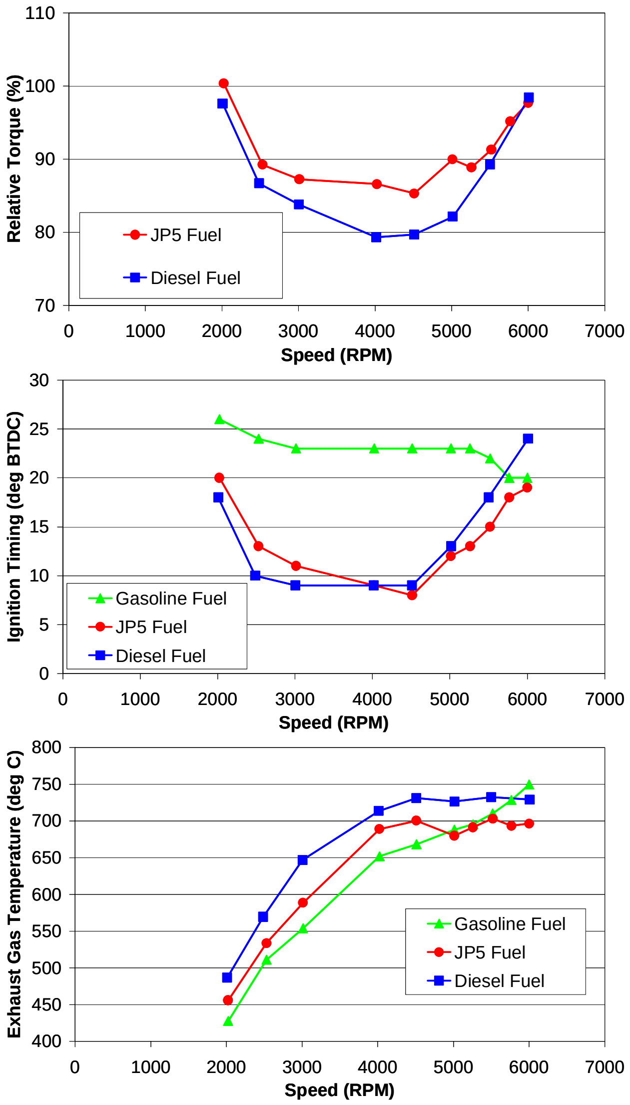


Fig.7 Full load performance comparison between gasoline baseline and air-assist DI engine on JP5 and diesel for 700cc 3-cylinder 2-stroke.

Fig.7 shows that at the mid engine speed, the ignition timing is more retarded for the JP5 and diesel fuels. This ignition advance is limited due to engine knocking. The retarded ignition timings also result in higher exhaust gas temperatures for the heavy fuel operation.

(2) Part Load Operation

Single cylinder 50cc engine results are shown in Fig. 8 at some typical part load points operating on gasoline, JP5 and diesel fuels. The fuel consumption levels are normalized against the brake specific fuel consumption achieved for the carbureted engine using gasoline.

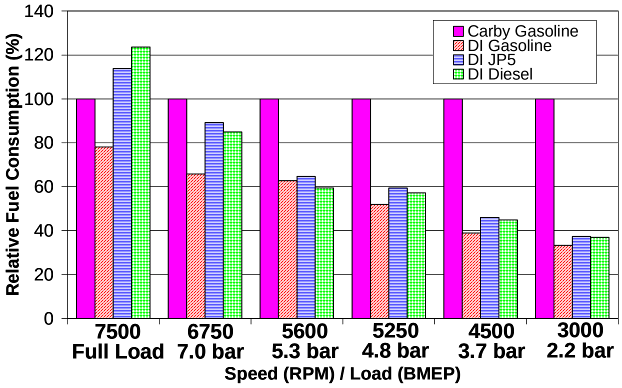


Fig.8 Part load fuel consumption comparison for a 50cc 2-stroke engine

Also shown below are results for a 700cc 3-cylinder engine running in gasoline, JP5 and diesel. The fuel consumption is compared against the gasoline air-assist DI results using lean, stratified operation. No homogeneous (port injection or carbureted) data was available for this engine.

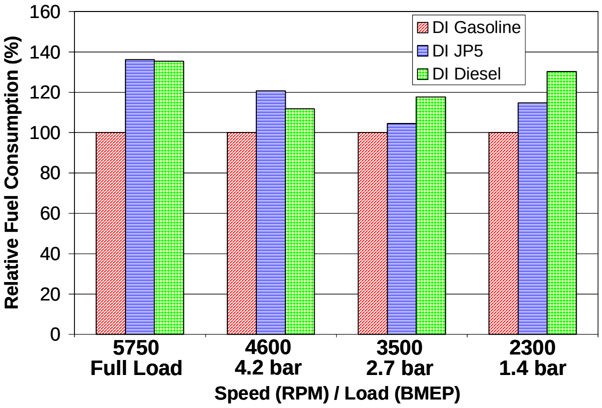


Fig.9 Part load fuel consumption comparison for 700cc 3-cylinder 2-stroke engine

The air-assist DI system operating with heavy fuel shows that much of the fuel consumption reduction enabled by the direct injection combustion system with gasoline is maintained for the heavy fuels. At most conditions, the fuel consumption is slightly degraded compared to the DI gasoline results. The largest increase in fuel consumption over the DI gasoline engine occurs at the highest loads. High load operation is limited by engine knock with the heavy fuels, so spark retard is required (see next section). This ignition retard in itself leads to higher specific fuel consumption. This effect can be compounded at the higher engine speeds by increased exhaust gas temperature, requiring increased enrichment to control the exhaust gas temperatures to acceptable levels.

(3) Starting and Cold Operation

A critical issue with heavy fuels in many spark ignition applications is the ability to start at cold ambient conditions and to then maintain satisfactory operation until the engine reaches normal operating conditions. In many circumstances, the fuel (and even engine) is pre-heated in order to have successful starting with heavy fuels. Due to the excellent atomization produced by the air-assist direct injection system, the system has been demonstrated to allow cold start down to -10deg C without the need for any external inputs. Fig.10 shows the results of start times versus ambient temperature for the application on a V6 2-stroke engine using JP5 fuel. The results show that a start time of approximately 4 seconds is achieved at -10°C, reducing to approximately 1 second once the temperature is higher than 0°C.

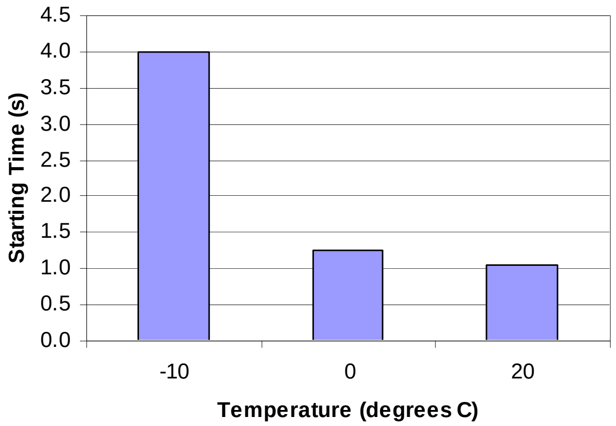


Fig.10 Cold starting time for 3000cc 2-stroke engine on JP5 versus ambient temperature

The attribute of the atomization also enables stable engine operation during the cold operation period.

3.2 4-STROKE ENGINE APPLICATIONS

More recently, development has been carried out on 4-stroke engine applications using the spray guided air-assist DI system. Whilst the approach has many similarities to that of the 2-stroke engine applications, there were specific considerations to be addressed for the 4-stroke engine application. These include the greater potential for engine pre-ignition and knock due to higher compression pressure and temperatures typically encountered on 4-stroke engine at full load. A further fundamental difference is that the containment of the fuel charge is largely carried out by the piston bowl design as opposed to the head combustion chamber as used in the 2-stroke engines.

(1) Full Load Operation

Fig.11 shows the full load performance of a 600cc, 2-cylinder air-assist DI engine using JP5 fuel. The full load torque is normalized against the full load torque from the DI engine running with gasoline.

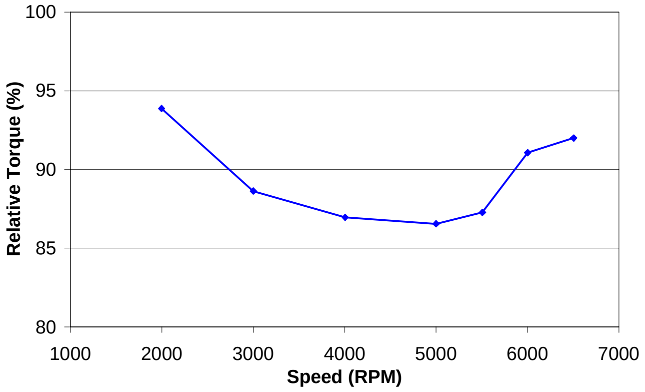


Fig.11 Full load performance comparison between air-assist DI engine on gasoline & JP5 for a 2-cylinder, 4-stroke engine

The results show very similar behavior to the 2-stroke engine performance comparisons, with a loss of full load torque at mid engine speeds of approximately 15%. The loss of torque is reduced to approximately 5% at the low and high engine speeds. The loss in full load performance is again due to combustion phasing effects from retarded ignition timings due to the higher knock propensity of the heavy fuels.

(2) Part Load Operation

Fig.12 shows part load fuel consumption and hydrocarbon emissions results from a typical 4-stroke engine operated with gasoline, JP5 and diesel. The baseline results with gasoline where obtained using the same air-assist DI combustion system with lean stratified operation.

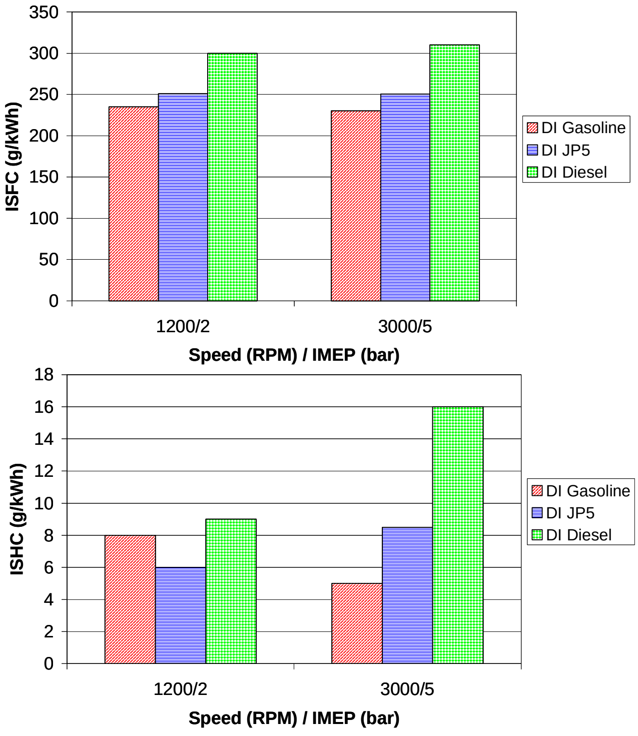


Fig.12 Part load fuel consumption and HC emissions comparison for 4-stroke engine

Similar to the 2-stroke engine findings, the introduction of heavy fuels leads to some increase in the specific fuel consumption relative to the air-assist DI gasoline stratified charge engine. The largest fuel consumption increases compared to the gasoline baseline occur at the higher speed and load operation. The diesel fuel is shown to have the highest increase in fuel consumption.

The hydrocarbon emissions are also shown to generally increase with heavy fuel operation. The absolute levels, however, are still reasonably respectable, especially for a lean burn direct injection engine.

(3) Start Up and Cold Operation

The strategies developed for the 2-stroke spark ignition direct injected engines have transferred well to the 4-stroke engine applications. Engine testing down to below -20°C has demonstrated good, consistent startability.

3.3 DURABILITY ISSUES

The heavy fuel application with spark ignition engines determined some specific engine durability issues that needed to be addressed. Some of the issues are common to both the 2 and 4-stroke engines, while others are specific to the engine type.

In the initial development of the 2-stroke spark ignition heavy fuel engines, both spark plug fouling and piston seizure/wear were evident. The problems were found to be more prevalent with the diesel based fuels. Solutions for diesel based fuels worked satisfactorily for the lighter faction kerosene based fuels.

(1) Spark Plug fouling

Initial engine developments, especially at light loads and start up conditions led to unacceptable spark plug fouling. This issue has addressed by a small amount of engine development including the following:

- Spark plug design/specification
- Combustion chamber design
- Calibration to minimize spark plug fouling by optimizing injection scheduling

Fig.13 shows the typical spark plug fouling encountered, and also shows the results after extended engine operation on diesel fuel with the optimized combustion chamber/calibration.

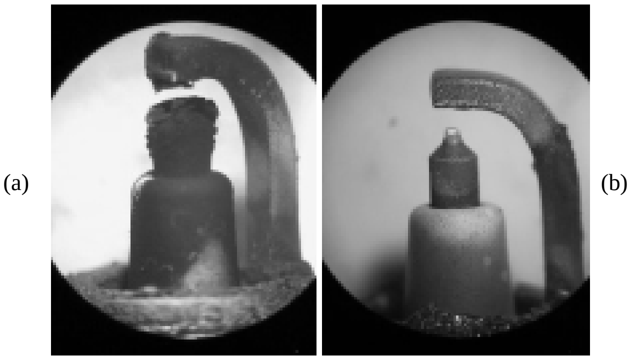


Fig.13 (a) Spark plug fouling with F76 (diesel) Fuel. (b) Optimised combustion system and calibration required to inhibit spark plug fouling

(2) Piston/Bore Seizure

Initial 2-stroke engine operation on diesel based fuels effected piston ring sticking within some 10 hours of operation. Subsequent to ring sticking, excessive wear and then piston/bore seizure would eventuate.

The piston bore/wear issue was found to be linked to the lack of sufficient lubrication on the bore and piston ring pack.

The typical lubrication on the 2-stroke engine relies, to some extent, on the fuel distributing the oil over the running surfaces within the engine. With diesel based fuels, this mechanism is changed, due to both the viscosity and evaporative properties of the various fuels.

To overcome this change, additional lubricant channels or ports were added to enable direct lubrication to the bore. As the direct injected engine utilizes a separate oil circuit/metering pump, this could be achieved without major changes to the lubrication system and without increasing the total oiling rate of the engine.

The results of the above two changes has shown significant improvement, with pistons/rings and bore in good condition with over 100 hours of operation. Fig.14 shows the initial wear/seizure problem and also the condition of the rings/piston with sufficient lubrication.

Seized piston due to ring sticking

Piston and rings in good condition

Fig.14 Piston condition without sufficient oil on bore and with improved oiling on bore and rings

(3) Oil Dilution

For the heavy fuel spark ignition application on 4-stroke engines, there is the potential to have large amount of oil dilution due to the lower volatility of the heavy fuels. The ingression of the fuel into the crankcase can result in excessive oil dilution. The oil dilution can be so fast that the oil quality is significantly affected, leading to low oil pressure and potential engine damage. As well, the oil level in the sump can rise very quickly, leading to oil carry-over in the crankcase ventilation circuit. Depending on the crankcase ventilation circuit, this can also lead to engine damage. This problem does obviously not arise for crankcase scavenged 2-stroke engines.

This issue is similar to those encountered in direct injection compression ignition diesel engines [7]. For spark ignited DI heavy fuel engines, similar approaches as is done for diesel engines can be adopted, which are aimed at limiting the amount of fuel contacting the bore surfaces through a combination of injected spray shape, piston design and injection timings. For the diesel engine, the design of the injector and piston bowl is such as to limit the amount of fuel which can digress to the bore walls. A similar approach was used for the 4-stroke spark ignition heavy fuel engine, with injector design and injection timing constraints in order to minimize fuel impingement at high fuelling levels.

Fig.15 shows results using optimized hardware and calibration to reduce the oil dilution effects. A small loss in torque is associated with the change due to the more retarded injection timings required to minimize wall wetting. By limiting the fuel impingement, acceptable oil dilution levels are able to be achieved

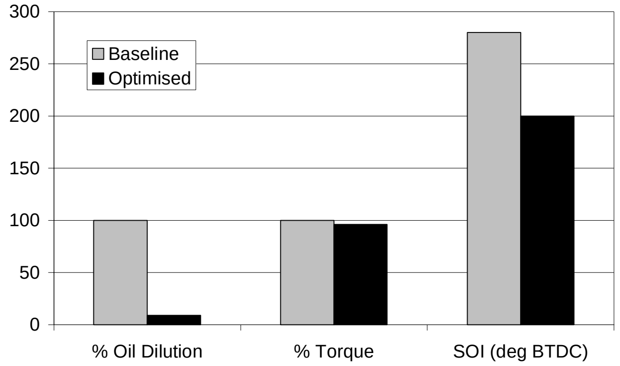


Fig.15 Oil dilution for 4-stroke heavy fuel engine on JP5

3.4 NEXT STEPS

Further development is underway that potentially will enable additional refinement and durability to both the 2 and 4-stroke spark ignition direct injected engine applications:

- Extended system and engine durability assessment to understand if there are any long term issues that require resolution
- Implementation of knock control and 'auto-fuel' sensing capability
- Development of cold start capability ultimately to the same environmental capabilities as production gasoline or diesel commercial applications

4. CONCLUSION

The following conclusions can be drawn from the information presented in this paper:

1. Spark ignition of heavy fuels such as JP5, JP8, F44 and F76 (diesel) is practical with minimum hardware change to an existing air-assist direct injection engine. Two 2-stroke engine applications have now been productionized.
2. The ADI system enables the multi-fuel 2-stroke engine to retain typically around 85% of the gasoline fuelled engine power, offering a significant power to weight advantage over equivalent powered naturally aspirated compression ignition engines.
3. The ADI system enables reliable cold start with heavy fuels down to -10 deg C.
4. The ADI system enables operator selected multi-fuel capability.
5. Future application of knock sensing and control strategies should allow 'automatic fuel sensing' capability.
6. Initial investigation has determined that the general strategies developed for the 2-stroke engine application transfers well to 4-stroke engines, with similar performance results.
7. By using existing high volume 2 and 4-stroke engines as the base engine, commercial aspects such as spare part distribution and servicing are established to support the multi-fuel engine user.

5. ACKNOWLEDGMENTS

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