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High Specific Power Output Direct Injection 2-Stroke Engine Applications

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Whilst Direct In-cylinder injection is now common in both the automotive and non-automotive markets, the very high performance 2-stroke engines pose specific challenges to the application of direct injection due to the increased fuelling levels, the high fuel turn down ratio requirements and the reduced fuel preparation times at high engine operating speeds.

In addition, a high performance 2-stroke engine will usually have a highly tuned scavenging system, which puts further demands on the fuel and combustion systems to achieve the desired performance. The fuel and combustion systems must also retain the low emissions to meet the relevant emissions legislation with a minimum level of aftertreatment. This paper briefly discusses the requirements for emissions reduction in high specific output 2-stroke engines, whether it is for a high performance motorcycle application that only uses relatively low loads across the emissions testing cycle or for a highly loaded and high speed snowmobile application.

This paper then reviews some of the specific challenges and latest developments for an Air Assisted Direct Injection (ADI) system and the accompanying combustion system to address the operating requirements of high performance and high speed 2-stroke engines.
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Keywords: Direct Injection, 2-stroke, Engine Combustion

1. INTRODUCTION

Direct in-cylinder fuel injection systems were introduced to the 2-stroke engine market in the mid 1990's, initially adapted and fitted to outboard engines and then followed by 50cc scooters in the early 2000's [1,2,3 and 4]. There are now significant volumes in the field, with reports and papers detailing the extended use and emissions capability [5] of these products.

The DI systems utilized for these motorcycle and recreational products, whilst sharing some level of heritage from the automotive direct injection applications, were specifically developed, or modified, for the non-automotive applications to address system cost and functionality requirements. These DI systems are now mature with both significant field experience and market acceptance.

The commercial applications of direct injection to-date has been on 2-stroke engines with brake mean effective pressure (BMEP) typically in the range of 5 to 9 bar as shown in Figure 1.

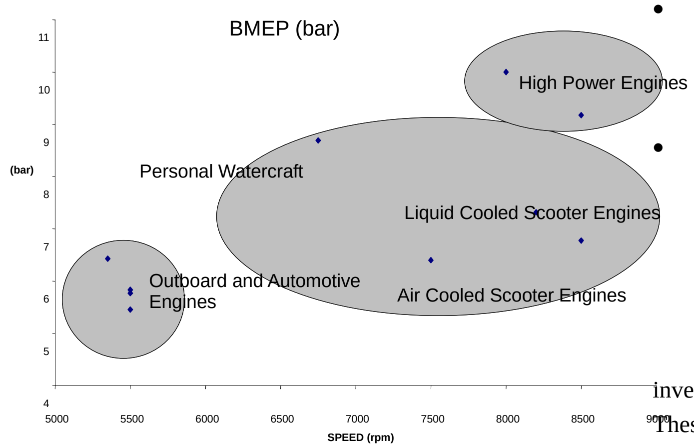

Figure 1 – Typical BMEP and engine speed characteristics for existing and possible DI 2-stroke applications

As shown, the highest BMEP application in production today is found in the Personal Water Craft applications (PWC) with a BMEP in the area of 8 to 9 bar at engine speeds close to 7000 rev/min. In comparison the outboard applications typically have a lower BMEP and engine speeds whereas the 50cc motorcycle applications operates at engine speeds up to 9000 rev/min with BMEP in the range of 6 to 8 bar. As the emissions legislation becomes both more stringent and broader in all aspects of the motorcycle and recreational product application, there has been a trend over the years to switch the powertrain to 4-stroke engine designs and move away from the carbureted 2-stroke. However it is evident that in some markets there is a clear demand for the continued benefits of the lighter and generally more powerful 2-stroke engine. In particular this demand has been strongest in the high performance snowmobile and motorcycle markets, where BMEP is in the region of 9 to 11 bar and engine speeds up to 9000 rev/min (as shown in Figure 1). This BMEP figure represents applications in excess of 130kW/liter, which is 20-30% higher than the current highest DI production application of 100kW/liter. As such there is a growing interest in the capability of direct injection systems to service these high power, or high BMEP 2-stroke applications, such as Enduro/Motocross motorcycles, snowmobiles and other off-road high performance applications.

The development of DI and combustion systems for high BMEP 2-stroke engines presents unique challenges beyond that addressed by today's production marine and motorcycle DI systems:

- High fuelling levels (>25 mg/cylinder) at high engine speeds for engine displacements up to 350cc/cylinder
- High fuel-turn down ratio requirements
- Highly tuned exhaust and scavenging systems
- Reduced fuel preparation and mixture time, due to the higher engine speed
- Requirement for very responsive drivability and throttle response
- Requirement to achieve satisfactory low speed/load combustion and acceptable emissions control
- Requirement to use as much as possible of existing production DI systems, given that generally the production volumes of the high performance engine are small, and cost considerations do not allow the development of an all new system configuration.

In recent years, efforts have been undertaken to investigate the requirements for high BMEP 2-stroke engines [6]. These engines are very application specific in terms of the product and the market requirement. For example, the emissions requirement for a high performance motocross application is significantly more stringent than that called for by the EPA for snowmobiles from 2010 onwards. Further, the operating regime across specific application test cycles can vary significantly.

Figure 2 – Time Weighted Usage shows a comparison of the time weighted load/speed conditions encountered during snowmobile and outboard motor/PWC testing as based on the ICOMIA and Snowmobile cycles [7, 8]. Also shown in Figure 2 is a steady state breakdown of the operating load/speeds of a high performance 4-stroke motorcycle (250 to 350cc displacement) operating over the ECE40 and EUDC test cycle, as called for under the Euro 3 regulations [9]. Likewise, there is a wide range of emissions requirements, as shown in APPENDIX 1 [7, 9]. Each application thus has specific challenges and understanding the trade off between performance and emissions is always a key factor to determine the final system configuration and calibration.

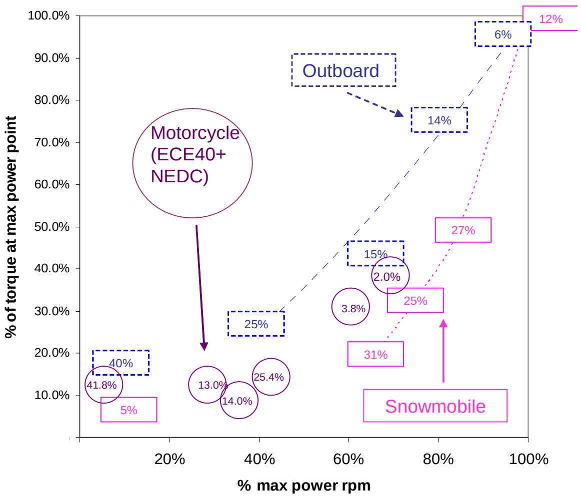

Figure 2 – Time Weighted Usage

This paper explores the extension of Air Assisted Direct

Injection applications to high performance and high engine speed motorcycle applications. The combustion chamber design is a key parameter as well as the injection system which must be able to deliver the required fuelling level in a short time period.

2. DEVELOPMENT PATH

During the ongoing development of the Orbital Combustion Systems (OCP) and applications, the use of the existing production ADI systems and combustion systems for high BMEP 2-stroke engines has indicated potential shortcomings including:

- **Combustion chamber design**: The typical combustion chamber used for best emissions control can lead to poor scavenging at very high power and high speeds, leading to potential rich misfire
- **Direct Injector design**: As power and fuelling levels increase, the requirement to inject high quantities of fuel in a short time period becomes paramount
- **System design and development**: This is somewhat product specific, depending on end user requirements and maximum engine speed.

The combustion chamber, followed by injector designs are the key development areas and these areas will be discussed in more detail.

2.1. COMBUSTION CHAMBER

During the development of the OCP system for the varying market applications a range of different combustion chambers have been developed.

In this paper the authors will refer to the current series production combustion chamber as the ‘closed’ design [10], which requires minimal alteration of the piston. Typically this chamber shows good emissions control with little compromise in power up to around 100 kW per liter.

The closed combustion chamber, as shown in Figure 3 – Closed Chamber, was initially developed for automotive 2-stroke engine applications. It was then transferred and scaled to the marine and motorcycle applications of that time.

This chamber was designed to maximize “charge containment” by utilizing the residual motion of the cylinder charge set up by the scavenge flow to both further stratify the cylinder mixture and direct the lighter fractions of the injector spray to the spark plug. This enables the transition from a highly stratified mixture through a relatively large transition phase to a nearly homogeneous mixture.

Depending upon the emissions requirement, the capacity of the cylinder and the emissions test duty cycle, a small bowl was added to the piston to enhance the charge containment. This combustion system was readily adaptable to different applications, being very tolerant of the base engine porting/scavenging arrangements.

Figure 3 – Closed Chamber

Whilst the lowest engine-out emissions and good drivability is obtained from this closed design chamber, it has the potential disadvantage at high engine speed and high BMEP operation of being more difficult to scavenge, creating excessive turbulence and poorer air utilization, due to a more apparent stratification of the charge at high engine speed. The power loss due to scavenging has generally been shown to be only a few percent in most applications, but the engine can be susceptible to rich misfire, primarily due to the shape of the chamber keeping an excessively rich mixture near the spark plug.

Figure 4 – Intermediate Chamber

With increasing power density, faster mixing of the fuel is required and alternative combustion chamber designs have been developed for this purpose. One such example is shown in Figure 4 – Intermediate Chamber. This chamber is currently used in ADI high performance PWC production applications. It has been modified on the exhaust port side to reduce the charge containment at high speed, whilst still retaining adequate containment at part load and good emissions control. The reduced turbulence and containment enables the engine to better utilize the cylinder charge, which generally enables significantly more fuel to be added before rich misfire occurs.

For the highest BMEP power application, it was found that further design changes were required to improve scavenging of the combustion chamber to take full advantage of the high scavenging flows, leading to the development of the open chamber, as shown in Figure 5 – Open Chamber. This chamber is easier to scavenge, has lower turbulence and offers better air utilization. Initial assessment of this type of combustion chamber on high performance marine products has demonstrated equivalent performance compared to the baseline carbureted engine. It should be noted that for very high BMEP applications, the performance compromise of the closed combustion chamber is significantly greater than that for the more typical 5-8 Bar BMEP engines.

Using an open chamber can potentially compromise emissions and run quality. To enhance the run quality and emissions, a bowl can be added in the piston, enabling a substantial emissions reduction compared to the carbureted engine, as shown in Figure 6 – Combustion Bowl in Piston.

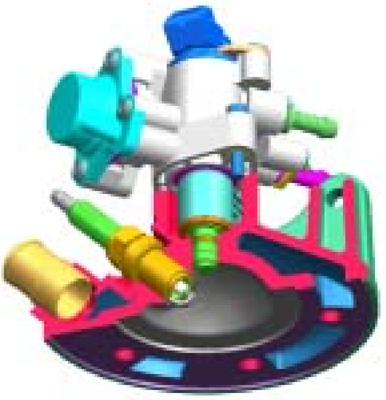

Figure 5 – Open Chamber

Whilst emissions control may not be as stringent as the closed chamber, in many high BMEP applications the engine-out emissions level requirement will allow for a compromise between high performance and emissions control. As discussed in the introduction, the weighting of the specific drive cycles for different market applications has a significant influence on the best overall compromise in the power versus emissions trade-off. Also in some cases there are good additional solutions involving exhaust aftertreatment as part of the overall emissions solution in combination with the application of an upgraded fuel system and combustion system.

Figure 6 – Combustion Bowl in Piston

2.2. INJECTOR DEVELOPMENT

In the development of Air Assisted DI system applications such as PWCs, which have a higher BMEP and high fuelling requirement than outboards or 50cc scooter engines, the general trend is to use a higher airflow injector for increasing performance. The PWC application uses a higher stroke (0.24mm vs 0.15mm for 50cc scooter), and narrower spray plume injector, with a penetration speed of around 60 m/s as opposed to the 50cc scooter application with a reduced stroke and penetration speed around 40 m/s. Figure 7 and Figure 8 – Injector Spray Plumes, show a comparison of the higher flow PWC injector to that of the standard 50cc scooter injector at equivalent fuelling levels and time after start of injection.

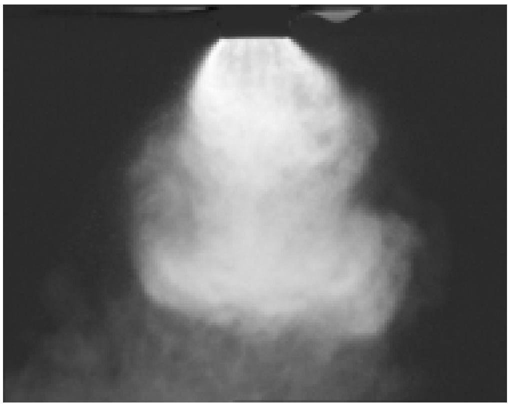

Figure 7 – Injector Spray – Motorcycle 0.15mm stroke Injector

Figure 8 – Injector Spray – PWC 0.24mm stroke Injector

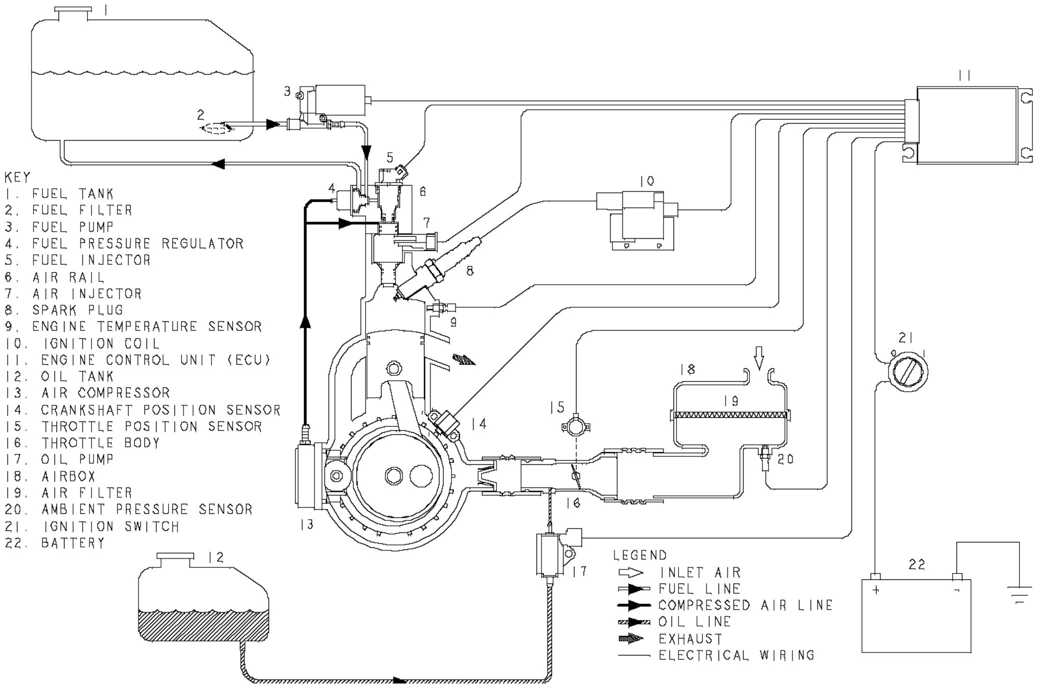

Figure 9 – EMS Schematic

Should it be required, injectors developed for high BMEP automotive applications in order to handle fuelling levels up to 100 mg/cycle, see references [11] & [12], could be applied to the high BMEP 2-stroke engine applications. However the initial developments discussed in this paper utilized the two production available injectors shown above.

3. HIGH BMEP MOTORCYCLE DEVELOPMENT

3.1. ENGINE DESCRIPTION

To confirm the capability of the ADI system for high BMEP motorcycle engine requirements, a standard carburetor fuelled engine was converted to ADI and fitted to the test bed. The test engine chosen to demonstrate the system was a single cylinder, liquid cooled engine with a peak power output in excess of 130kW/liter at 8500 rev/min. In addition to power and torque, air/fuel ratio was measured using a UEGO wide band sensor, and a pressure transducer fitted to the combustion chamber.

For this initial investigation the open chamber combustion system was used, along with the PWC style air injector.

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One of the key objectives of this development program was to maintain as much in common as possible with the existing commercialized ADI systems.

3.2. ENGINE MANAGEMENT SYSTEM

The engine management system (EMS) utilized for the test engine was based upon the production Air Assisted DI system already supplied to Peugeot, Piaggio and Aprilia [13]. The fuel system was modified for this higher power application by sourcing a high flow fuel injector, which provided sufficient turn-down for idle condition and WOT operation (enabled by the independent fuel metering of the Air Assisted DI system). In this case an existing Siemens Deka 2 fuel injector, with a delivery of 4 g/sec @ 180 kPa fuel differential was used, which provided a fuelling range from 1.8 mg/cycle to 26 mg/cycle, a ratio of 14:1. A schematic of the overall system is shown in Figure 9 – EMS Schematic.

As weight and electrical power consumption are critical on these types of high performance applications, it was not practical to use an automotive style fuel pump. A variant of the current standard piston fuel pump used for the current production motorcycle/scooter applications was also developed, the major change being the use of a 7mm diameter plunger vs a standard 4mm diameter plunger. The motor size was increased from 4 to 9.4 Watts with the fuel pump current draw increasing from 0.4 to 1.5A at 12V, which is still acceptable for a motorcycle charging system.

3.3. BASELINE TESTING

During baseline carburetor engine testing, it was established that engine power had to be determined transiently. The method chosen was to run the engine at WOT at 3000 rpm and increase the speed gradually to its maximum over about 30 seconds. When maximum speed was reached, the ignition was cut and the engine allowed to stop. All parameters were logged at a frequency of 10 Hz.

The results of this type of testing correlated well with the manufacturer’s data and were accepted as a baseline, shown in Figure 10 – Carbureted vs DI Performance. In addition to the normal measured parameters, a UEGO was used to measure air/fuel ratio, due to the relatively fast response time.

3.4. CONVERSION TO DIRECT INJECTION

The engine was then converted to Air Assisted Direct Injection. Essentially the upgraded production scooter system was fitted with the following exceptions:

- The compressor was not fitted – shop air was used for the injector air supply at 5.5bar
- To enable investigations of the influence of combined port injection and direct injection, a port injection system was fitted upstream of the intake reed valves
- The existing carburetor was used as a throttle body to reduce the changes from the base engine
- A higher air flow injector, as used on the PWCs, was installed.

3.5. DIRECT INJECTION POWER TESTING

The calibration method used for power testing involved offsetting each parameter and entering the maps into the ECU. A transient test was run for each map, the torque for each speed compared and the optimal setting entered into the map. The results, as shown in Figure 10 – Carbureted vs DI Performance, demonstrated that the open chamber could match the baseline carbureted engine for performance.

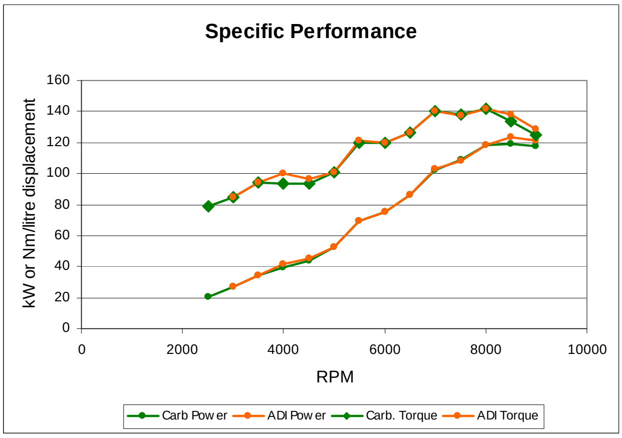

Figure 10 – Carbureted vs DI Performance

A further assessment was carried out with the addition of a 27mm diameter bowl (as shown in Figure 6) in the piston. The results of this testing indicated a very small compromise on the WOT performance, as shown in Figure 11 – Effect of Bowl in Piston. However the benefits to part load emissions are very significant as discussed in section 3.7.

As the compression ratio was not adjusted to compensate for the addition of the piston bowl, it is likely that some of this small reduction in torque is due to the lower compression ratio.

3.6. WIDE OPEN THROTTLE AIR FUEL RATIO SENSITIVITY

As engine airflow for these high performance 2-stroke engines can change significantly with different exhaust tuning caused by variations in exhaust pipe designs and temperatures, along with the EMS and engine variations, the sensitivity to air fuel ratio was investigated. As most of the concern is rich misfire, a 15% increase in fuelling was added to allow for these variations, by mapping extra fuel in the ECU.

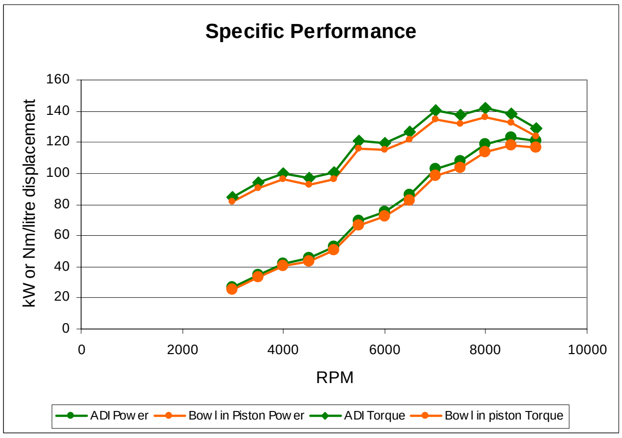

Figure 11 – Effect of Bowl in Piston

Specific power and torque data for this investigation are shown in Figure 12 – Effect of 15% additional fuel with Open Chamber Combustion System, illustrates no significant performance change with this open chamber hardware configuration.

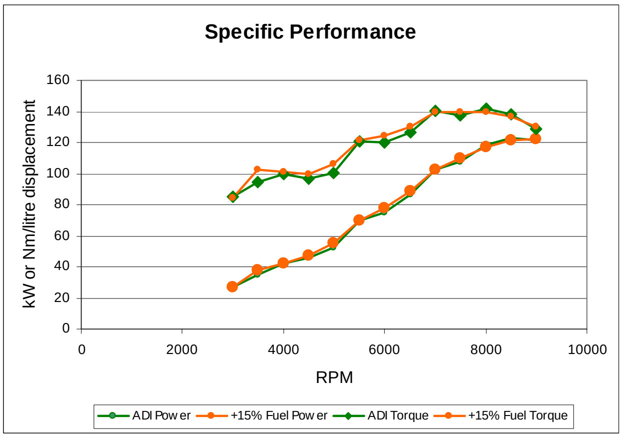

Figure 12 – Effect of 15% additional fuel with Open Chamber Combustion System

3.7. EMISSIONS AND FUEL CONSUMPTION

In order to obtain an indication of the emissions capability and fuel economy of this ADI conversion, a steady state test simulating the ECE40 and EUDC test cycles were also developed. The steady state load/speed points are estimated by logging speeds and loads though the certification test at 0.5 Hz frequency, then plotting on a scatter chart. The selected test points for simulation of the Euro 2 and 3 test cycles with this motorcycle application are shown in Table 1.

Experiments utilizing these test points were performed with both the open chamber and then the open chamber with the small bowl added to the piston to understand the power vs emissions capabilities. The results are shown in Table 2 and are to be compared with the forthcoming Euro 3 emissions requirements [7] for > 150cc motorcycle as shown in Table 3.

Point	1	2	3	4	5	6
Speed	1500	2850	3850	4380	6520	7125
Load (Nm)	idle	4.00	3.21	5.30	10.40	13.14
Time Weightings						
Euro 2	371	96	228	96		
Euro 3	675	210	226	409	61	32

Table 1 – Steady state test points and time weightings for Euro 2 and Euro 3 motorcycle

	Euro 2 ADI Open Chamber	Euro 3 ADI Open Chamber	Euro 2 ADI Open Chamber (bowl in piston)	Euro 3 ADI Open Chamber (bowl in piston)
HC (g/km)	5.5	3.1	1.6	1.1
CO (g/km)	2.5	2.8	2.2	2.2
NOx (g/km)	0.02	0.02	0.12	0.14
FC (g/km)	28	23	20	18

Table 2 – Composite Emissions

	Euro 2	Euro 3
HC (g/km)	1.0	0.3
CO (g/km)	5.5	2.0
NOx (g/km)	0.3	0.15

Table 3 – Emissions Standards > 150cc

These initial results indicate the likely range of engine out emissions vs the absolute performance level of the engine for the Euro 3 emissions requirement. The significant reduction in HC emissions (64% reduction for Euro 3 simulation) with the addition of a small piston bowl is very significant and is due to the improved fuel containment of the bowl over this lightly loaded motorcycle test cycle. In order to meet the Euro 3 tailpipe emissions there would still be a need for a level of exhaust aftertreatment to meet the HC target specifically. The application of a catalyst system to achieve a 75% conversion efficiency for the oxidation of HC is considered quite feasible, with minimal WOT performance loss.

As discussed previously, the emissions requirement for different recreational products is very application specific, and the final system specification will depend upon the correct combination of combustion chamber, piston bowl and fuel system.

3.8. NEXT STEPS

Further development is required to understand the full trade offs of emissions vs performance for the very high BMEP applications in order to develop the overall system definition required to meet the regulated requirements of emissions and drive-by noise of a specific application. Further development will include optimization of the combustion chamber, piston bowl and air injector to maximize power, yet minimize the emissions load for the aftertreatment system.

4. CONCLUSION

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

- Testing determined that with an open combustion configuration, the ADI systems could match the WOT power and torque of the standard carbureted high BMEP motorcycle 2-stroke engine with specific power in excess of 130kW/liter
- The open combustion chamber and ADI injection system will tolerate at least a 15% rich shift in fuelling, enabling a good allowance for system tolerances, and operating conditions
- Steady State testing, simulating the EUDC drive cycle indicates that with aftertreatment, there is the potential to achieve Euro 3 requirements with a specific configuration of the combustion chamber and piston bowl whilst maintaining the high BMEP performance capability. This must be confirmed by a full vehicle application and testing.

5. ACKNOWLEDGMENT

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Nomenclature

ADI – Air Assisted Direct Injection

BMEP – Brake Mean Effective Pressure

EMS – Engine Management System

PWC – Personal Watercraft

UEGO – Exhaust Oxygen Sensor

8. APPENDIX 1

Snowmobile Emissions Requirements

Phase	Model Year	Phase-In (Percent)	Emission Stds			Max allowed family emission limits		
			HC	HC+NOx	CO	HC	HC+NOX	CO
Phase 1	2006	50	100	na	275			
Phase 1	2007 - 2009	100	100	na	275			
Phase 2	2010 and 2011	100	75	na	275			
Phase 3	2012 and later	100	75	*	**	150	165	400

* Corporate Ave HC+N)X < 90 gm/kw hr
** Corporate Ave CO<275 gm/kw hr

Euro 3 Motorcycle Requirements

Region	Test Cycle	Emissions Limits (g/km) (2)	Introduction Date
Europe	Modified Driving Cycle ECE 40	0.8HC 0.15 NOx 2.0CO < 150 cc 0.3HC 0.15 NOx 2.0 CO > 150cc	Stage 3 (2-stroke/4-stroke)