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Development of a Compression Pressurized Direct Fuel Injection System for Retrofit to Two-Stroke Engines

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ABSTRACT

Small displacement carbureted, crankcase-scavenged, two-stroke engines are commonly used for transportation needs in developing countries (Iyer 2000). The high emissions characteristic of this engine design creates localized acute air pollution problems and contributes significantly to global air pollution (Gorham 2002). A compression pressurized direct fuel injection system (CPDI) has been proposed as a lower cost alternative to the common air blast direct injection system (ABDI). This paper describes the application of the CPDI system as a retrofit to a two-stroke engine typical of those used in “tricycle” transports in the Philippines. Power production, emissions, and fuel consumption for the original carbureted engine, the ABDI system and the CPDI system are also compared. The DI systems show a significant reduction in both hydrocarbons (88% reduction for the ABDI system and 86% reduction for the CPDI system) and carbon monoxide (49% for the air blast system, 83% for the compression pressurized system), and similar power compared to the carbureted engine.

INTRODUCTION: ABDI AND CPDI

The air blast direct injection system, pioneered by Orbital Engine Company (Huston et al. 1998), has successfully been applied as a retrofit to small two-stroke engines for the purpose of improving emissions via reduction of fuel short-circuiting (Willson 2002). In the ABDI system (figure 1), fuel is injected into a cavity in an air rail, which is separated from the combustion chamber by an outwardly opening, solenoid actuated, poppet valve called the “blast valve”. Pressurized air is also provided to the air rail by a mechanical pump, which is driven by the crankshaft. When the blast valve is opened the air “blasts” the fuel into the combustion chamber, finely atomizing it as it enters the combustion chamber. While this system is successful at reducing the hydrocarbon (HC) and carbon monoxide (CO) emissions of the engine, the intrusiveness of the air pump presents a challenge for retrofit applications. The rest of the components can be bolted on, either replacing an existing part (such as the head), or in an arbitrary location (such as the fuel pump). The air pump, however, requires durable mounting to the engine case and coupling to the spinning crankshaft.

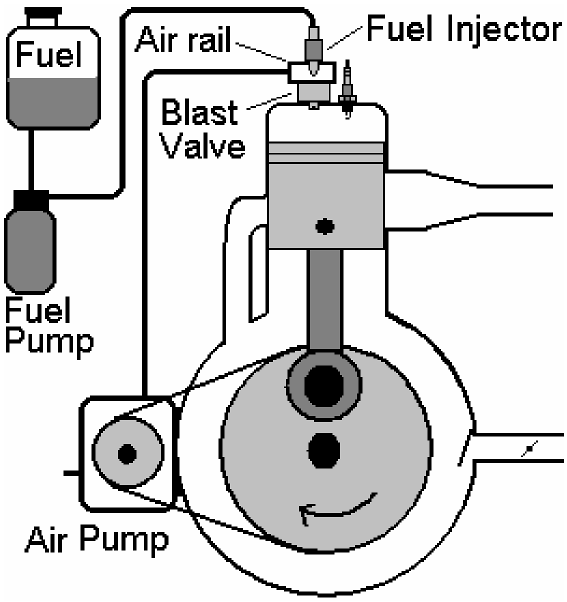

FIGURE 1 Schematic of an air blast direct injection system on a two-stroke engine. Note the air pump, which is driven by the crankshaft.

One way to eliminate the air pump is to modify the ABDI system so that pressure for the blasting of the fuel is extracted from the combustion chamber during the compression stroke. This technique was first proposed by AVL List GMBH of Austria (Fraidl 1996), and later refined by Orbital Engine Corporation of Australia (Leighton 1994). The compression pressurized direct injection system (figure 2) uses most of the same components as the ABDI system, however, now the blast valve must do a double duty as it is responsible for the blasting of the fuel, and re-charging of the mixing cavity which replaces the air rail.

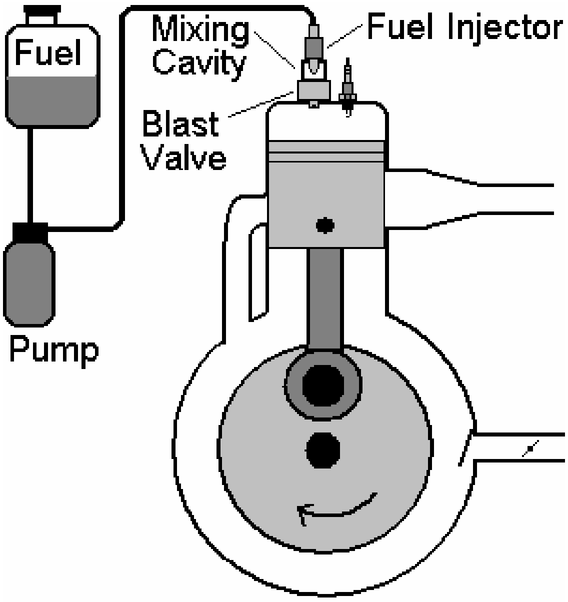

FIGURE 2 Schematic of a compression pressurized direct injection system on a two-stroke engine. The mixing cavity is pressurized from the combustion chamber during the compression stroke.

There are three phases to CPDI operation: cavity pressurization (recharge), fuel introduction, and cavity discharge (blast) to the combustion chamber. The pressurization phase takes place during the compression stroke and is completed before ignition. The blast valve is held open, and the compressed gases from the combustion chamber are admitted into the mixing cavity (figure 3). Once the mixing cavity has attained the appropriate pressure, 500 kPa for example, the blast valve is closed, sealing the mixing cavity.

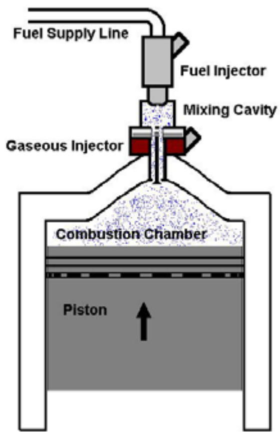

FIGURE 3 Blast valve is held open during compression stroke to pressurize the mixing cavity.

Once the blast valve is closed fuel may be injected into the mixing cavity while the engine is in the combustion, expansion or exhaust portion of the cycle. The fuel is injected directly at the back of the blast valve (figure 4). As the gases in the mixing cavity are still hot from compression, some fuel may vaporize, however much of may remain as liquid droplets, or a liquid film on the back of the blast valve.

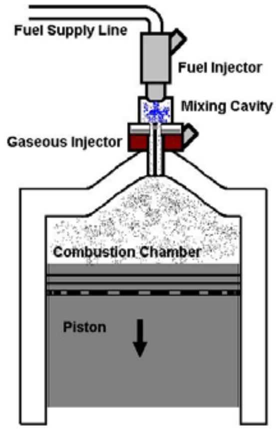

FIGURE 4 Fuel is injected into the mixing cavity, partially evaporating, while the blast valve is held closed.

Once scavenging is complete and the exhaust port is closed, the blast valve is again opened. As the pressure of the mixing cavity (approximately 500 kPa) is greater then the pressure of the combustion chamber (approximately 120 kPa) the contents of the mixing cavity are "blast" into the combustion chamber. Any remaining fuel droplets are finely atomized in the strong shear between the injected gases and the combustion chamber gases (figure 5).

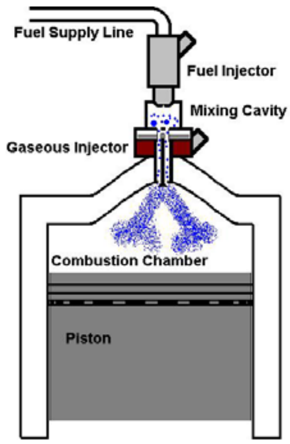

FIGURE 5 The fuel is blast into the combustion chamber at the beginning of the subsequent compression stroke.

CPDI: SINGLE VS. DUAL VALVE ACTUATION

In the CPDI design the blast valve may either be actuated twice per revolution (CPDI-2) of the engine, with separate "blast" and "recharge" events, or the two steps may be combined in a single actuation which holds the valve open continuously from the beginning of the blast event to the end of the recharge event (CPDI-1). The CPDI-1 mode of operation has the advantage of requiring no additional electronic hardware, as the existing ABDI system's electronic control unit (ECU) can be used to actuate the blast valve once per cycle. Inherent in the CPDI-1 technique, however, is the possibility of injecting fuel into the combustion chamber at relatively low differential pressures, thereby potentially degrading the atomization quality. The CPDI-2 technique has the ability to avoid this low-pressure injection by closing the blast valve while the pressure differential is still relatively high, and only reopening it for recharge after the pressure of the combustion chamber has exceeded that of the mixing cavity. The CPDI-2 technique, however, requires additional circuitry to operate the valve twice per revolution. We therefore used a separate computer system and injector driver circuit for operation of the blast valve in the CPDI-2 mode. In CPDI-2 mode, all of the other functions, such as ignition, liquid fuel injector actuation, fuel and oil pump operation, and throttle sensing, were performed by the ABDI ECU.

ENGINE MODIFICATIONS: KAWASAKI HD-III

As the focus of our project was the reduction of vehicular emissions in developing countries, we selected the Kawasaki HD-III 125cc two-stroke motorcycle for our modifications. This is the most common motorcycle in use in the Philippines, where it is often fitted with a sidecar, and used as a taxi, called a "tricycle" (figure 6).

FIGURE 6 Kawasaki HD-III "tricycle" with sidecar at CSU's Engines and Energy Conversion Laboratory.

The majority of the fuel injection components (fuel pump, fuel rail, fuel injector, blast valve, oil pump, ECU, air pump, generator, index sensor) came from an Aprilia Scarabeo motor scooter, which uses an Orbital ABDI system. The side case of the engine was modified to accept the air pump, and an air pump driving cam for ABDI system testing (figure 7). An aluminum head was machined which accepted the ABDI hardware. The combustion chamber shape was designed based on a shape used by Orbital in similar displacement engines.

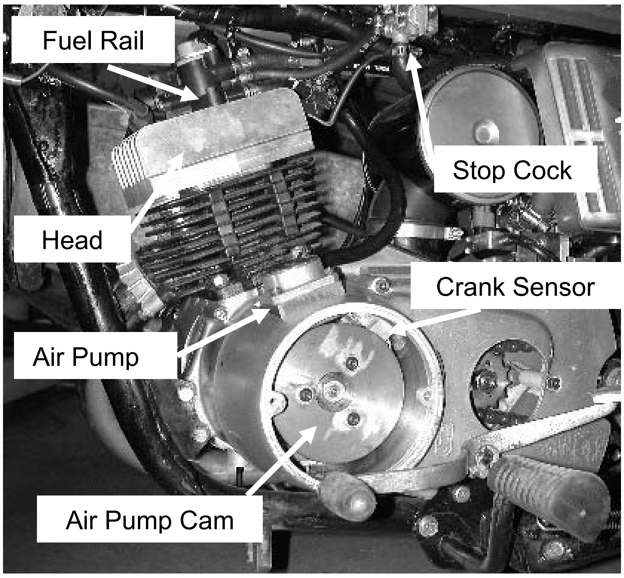

FIGURE 7 Kawasaki HD-III with ABDI modification.

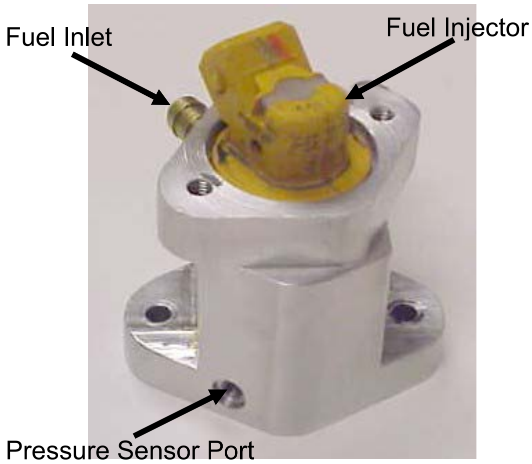

FIGURE 8 The CPDI mixing cavity replaces the fuel rail of the ABDI system. The skew of the top flange allows easier access to the lower flange's head bolts.

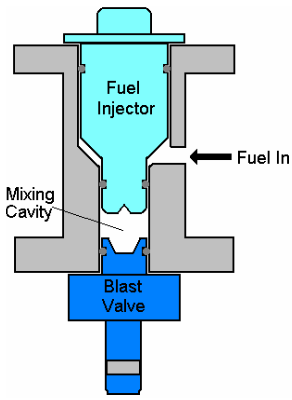

FIGURE 9 Schematic of the CPDI mixing cavity. Cavity is formed in the space between the two injectors.

The mixing cavity of the CPDI system was machined out of aluminum as well (figure 8). It was designed to work with the ABDI head and injectors. The mixing cavity volume is formed in the space between the fuel injector and the blast valve (figure 9). The volume of the mixing cavity could be varied by displacing one or both of the injectors outwards using shims. We selected a mixing cavity volume of 1.44cc for the results presented here.

TEST APPARATUS

The drive sprocket of the engine was connected directly to a 30 kW RAJ eddy current dynamometer to measure the engine's torque and power (figure 10). Emissions of HC, CO, CO_2, NO_X and O_2 were measured with a Vetronix PXA-1100 Gas Analyzer. The output of the analyzer for HC was calibrated to hexane. Pressures in the mixing cavity and combustion chamber were measured using Kistler type 6052B1 high temperature pressure sensors.

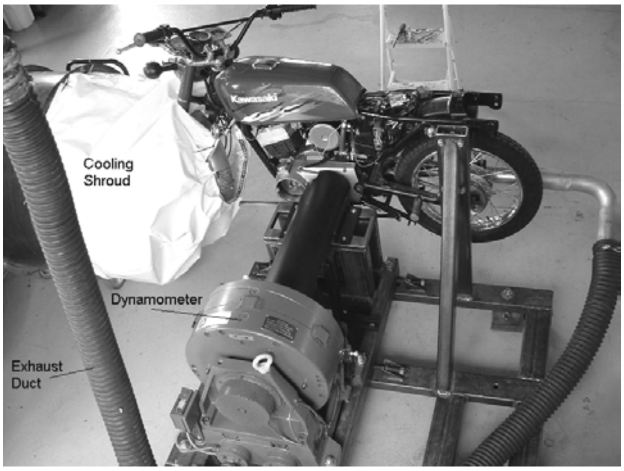

FIGURE 10 Motorcycle on the test stand. The dynamometer connects to the output sprocket. The cooling shroud directs air from a large fan for cooling.

RESULTS

Initially, the ABDI system was installed and tuned in. Initial fuel and valve timing maps had been provided by Orbital, and were modified based on engine power and emissions results. The CPDI system used the same fuel map as the ABDI system. Initial valve timings for the CPDI system were based on an engine simulation model, WAVE, previously described (Gitano-Briggs 2003). The first testing of the CPDI system consisted of verifying the mixing cavity pressurization while the engine was being motored. Figure 11 shows pressure in the combustion chamber and the mixing cavity while the engine is spun at 700 rpm for the CPDI-1 system with the ignition disabled. The mixing cavity maintains a pressure of approximately 400 kPa, which drops to approximately 200 kPa during the "blast" phase, and is recharged back up to 400 kPa during the compression stroke. The Start Of Blast (SOB) is 80°BTDC and the End Of Recharge (EOR) is 40°BTDC.

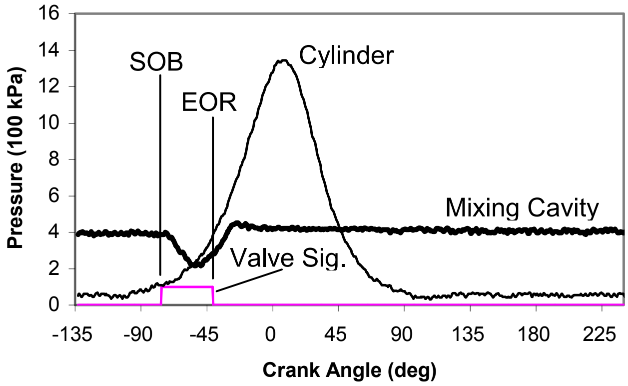

FIGURE 11 Pressure in the mixing cavity and combustion chamber during motoring at 700 rpm for the CPDI-1 system. Valve signal is shown for reference only.

The CPDI-2 system was also tested while motoring the engine (figure 12). For this plot the valve timings were: SOB = 80°, End Of Blast (EOB) = 70°, Start Of Recharge (SOR) = 45°, and EOR = 35° BTDC. Here we can clearly see the separation of the blast and recharge phases. A mechanical delay in the opening and closing of the valve can be seen in the figures. The opening delay is approximately 800μs, while the closing delay requires significantly more time, approximately 4 ms, due to the relatively weak return force of the valve.

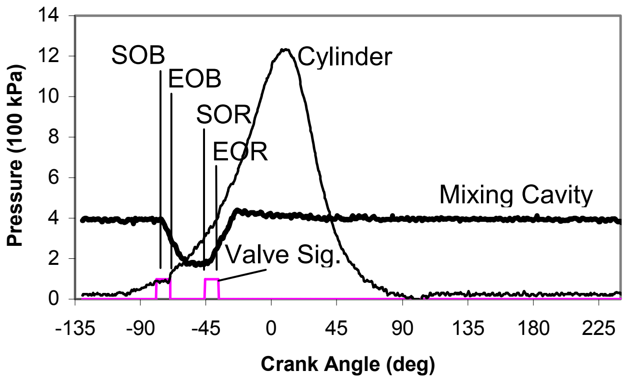

FIGURE 12 Pressures in the mixing cavity and combustion chamber during motoring at 700 rpm for the CPDI-2 system. Valve signal is for reference only.

As the EOR timing is retarded, or moved closer to TDC, the ultimate mixing cavity pressure will increase. This is one of the fundamental factors in tuning the CPDI systems. To measure this, the CPDI-2 system was motored at a speed of 700 rpm while moving the EOR timing (figure 13). To reduce the sensitivity of the results to SOR the valve was held open for a relatively long recharge of 20°.

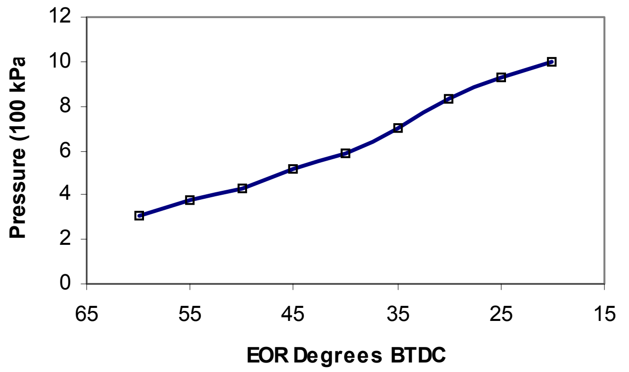

FIGURE 13 Ultimate mixing cavity pressure as a function of EOR for the CPDI-2 system motoring at 700 rpm.

During startup the mixing cavity will initially be depressurized. The ECU has special code to allow for compression pressurization of the air rail in the ABDI system on the first few revolutions of the engine during startup. Our CPDI-2 system was not so sophisticated, however, with the relatively small mixing cavity volume of 1.44cc the CPDI-2 system was able to pressurize the mixing cavity in the first few revolutions of a kick-start (figure 14).

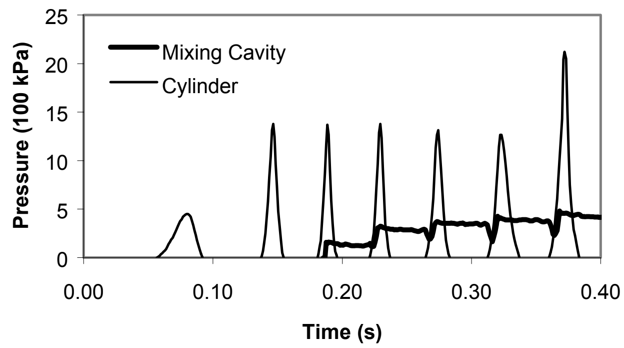

FIGURE 14 Pressure in the mixing cavity and combustion chamber during kick starting of the CPDI-2 system. The high pressure of the final peak indicates successful combustion, i.e. the engine started.

While the engine was operable in both the CPDI-1 and CPDI-2 modes with the initial blast valve timings from the model, slight tuning was required to achieve a smooth and consistent idle. Figure 15 is a comparison of the idle combustion chamber pressure for a number of revolutions for the CPDI-1, ABDI and carbureted systems. The ABDI system has the most consistent peak combustion pressures. Despite the fact that the carbureted system audibly sounded smooth, it was actually experiencing a late burn on every fourth cycle, as evidenced by the broad peaks with slightly higher amplitude, and completely missing the intervening cycles.

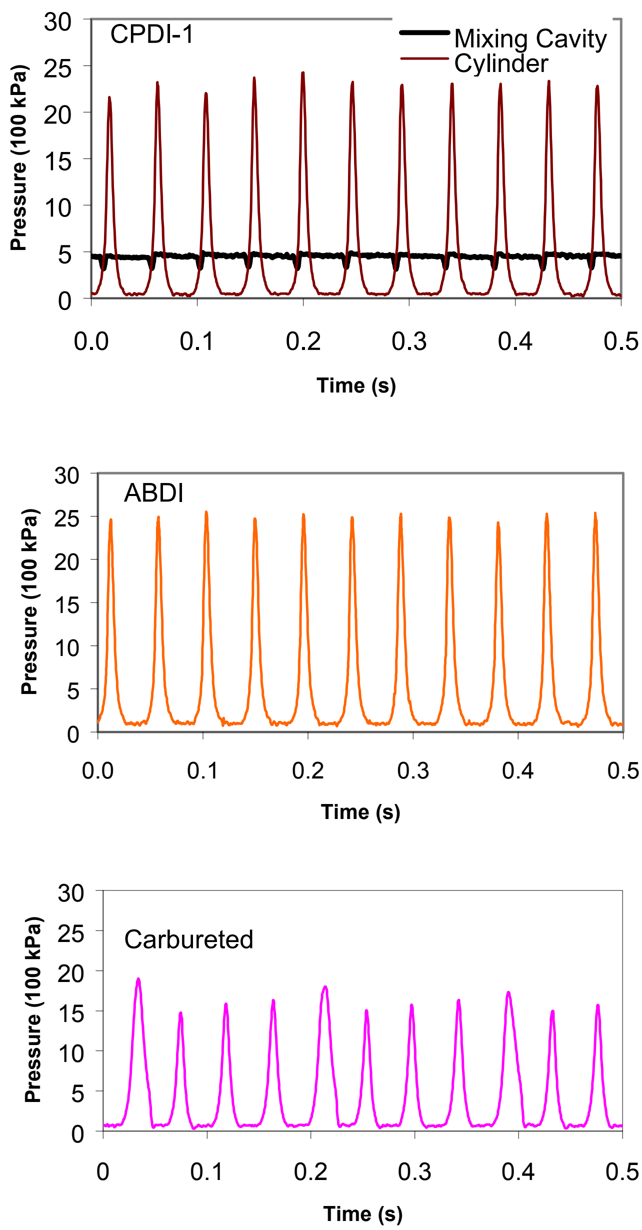

FIGURE 15 Combustion pressures from the CPDI-1, ABDI and carbureted systems for several revolutions during idle at approximately 1300 rpm.

In order to operate the CPDI systems under load, the blast timings had to be significantly advanced to provide a more homogenous mixture in the combustion chamber. This differed significantly from the model's predictions, which had assumed nearly instantaneous mixing of the injected fuel, and therefore gave more retarded blast timings. A typical pressure trace taken with the CPDI-2 engine loaded is seen in figure 16. The engine was producing 7.7 Nm of torque and about 3.6 kW of power with timings of: SOB = 210°, EOB = 113°, SOR = 45°, and EOR = 39° BTDC.

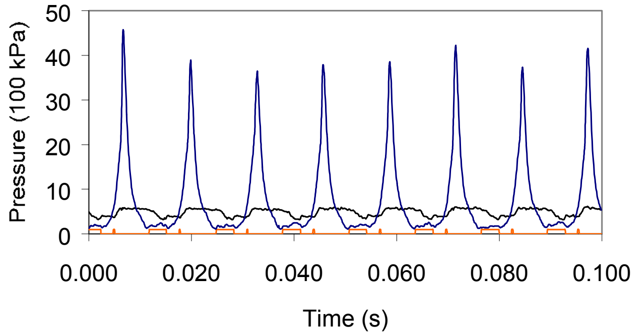

FIGURE 16 Pressure in the mixing cavity and combustion chamber for the CPDI-2 system at 4700 rpm, WOT. SOB is advanced for more homogenous mixing.

Due to ECU timing constraints, which limited the maximum valve actuation duration to 4.8 ms, it was not possible to run the CPDI-1 system with optimized timings over the entire range desired. Additionally, in order to achieve reasonable timing control of the CPDI-2 system the maximum SOB advance was limited to 220° BTDC. Power and torque curves for the CPDI-1 (curves) and the CPDI-2 (points) are shown in figure 17. The CPDI-1 system produced a peak power of 4.5 kW at 6200 rpm, and a maximum torque of 7.8 Nm at 4500 rpm, while the maximum power measured for the CPDI-2 system was 4.3 kW at 5600 rpm, and maximum torque was 8.2 Nm at 4200 rpm.

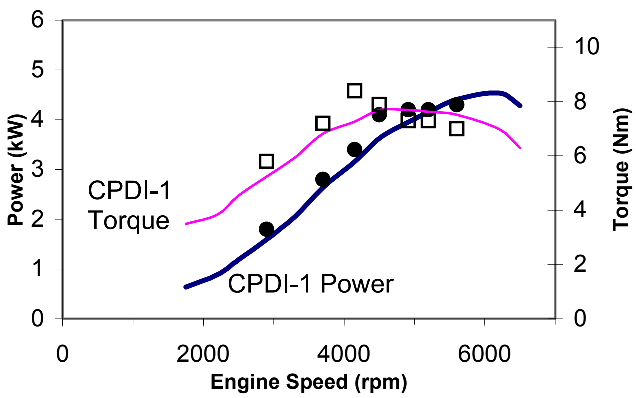

FIGURE 17 Power and torque for the CPDI-1 system (solid lines) and the CPDI-2 system (points) at WOT.

To quantify the emissions improvements, emissions and power were measured for the carbureted, ABDI, and CPDI systems at a number of operating points of engine speed and throttle position: (Idle, 2500 rpm-40% throttle, 3500-40%, 3500-80%, 4000-40%, 4500-60%, 4500-80%, 4500-100%, and 5500-100%). Not all operating points were measured for both of the CPDI systems, but at each operating point a measurement was taken from at least one of the CPDI techniques. The direct injection systems were not operated at a stoichiometric air/fuel ratio, as this caused significant pre-ignition or knock. The DI systems were operated rich (air/fuel ratio of approximately 13:1) at 80% throttle and above, for increased power. Below 80% throttle the DI systems were operated slightly lean (air/fuel ratio of approximately 22:1) for improved emissions. Power production for the DI systems was typically slightly better than the carbureted system at each operating point.

Hydrocarbon emissions (figure 18) in general show in increase with engine power production for all of the fuel delivery techniques. Additionally it is clear that the DI techniques emit significantly less HC than the carbureted version. The highest HC emissions for the carbureted engine are 5250ppm at idle, while the ABDI system emitted 250ppm HC, and the CPDI-1 system emitted 200ppm HC at idle. The inconsistent combustion noted in figure 15 undoubtedly contributes to the HC emissions number for the carbureted system.

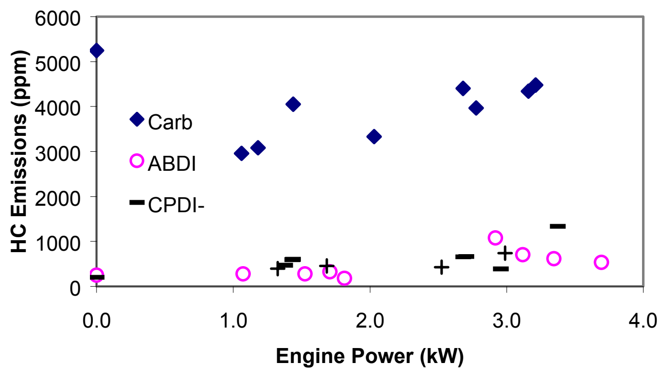

FIGURE 18 HC emissions for the various models at identical operating speeds and throttle settings versus engine break power. Emissions numbers at zero power are for idle.

Carbon monoxide emissions are similarly compared in figure 19. The carbureted engine has significantly higher CO emissions than the DI techniques at the lower power levels, where the DI techniques are operating in the lean mode. At higher power demands, the DI systems switch to rich mode operation, and the CO emissions of the ABDI system increase significantly. The CPDI systems, however, have significantly lower CO emissions at the higher power levels than the ABDI system.

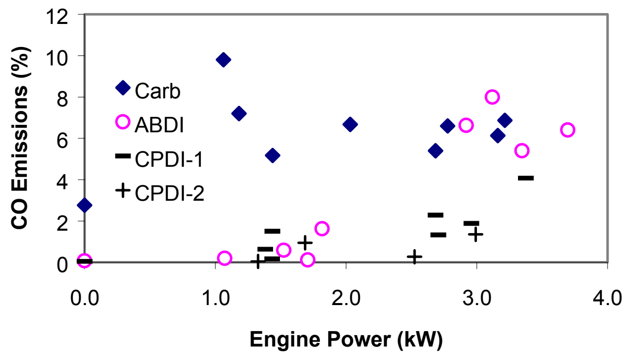

FIGURE 19 CO emissions for the various models.

Finally oxides of nitrogen were similarly compared between the various techniques (figure 20). Due to the large amounts of recirculated exhaust gasses, we would anticipate low NO_X emissions for the carbureted system. As combustion efficiency and temperatures are increased with the DI systems, it is expected that the NO_X emissions will also increase.

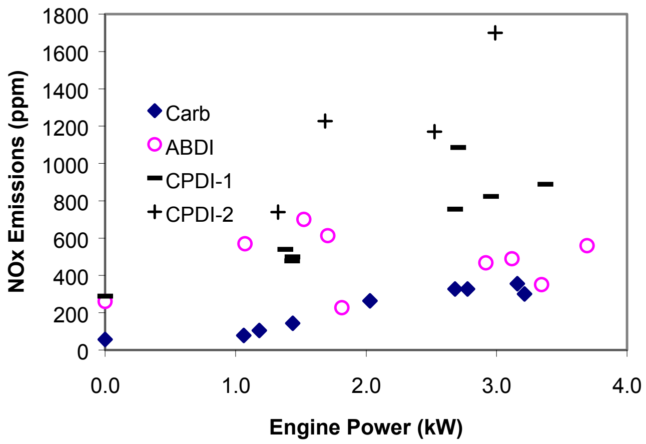

FIGURE 20 NO_X emissions comparison for the various techniques.

At low power demands the DI systems are running in lean mode, resulting in higher NO_X emissions. At higher power demands, the NO_X emissions of the ABDI system approaches that of the carbureted system, however, the CPDI systems are still producing significantly higher levels of NO_X even when operated in the rich mode.

The low CO emissions and high NO_X emissions of the CPDI systems at high power demands indicates that the CPDI systems are running leaner than the ABDI system under similar loads. This is very likely due to the mixing cavity pressure dependence of the fuel delivery. In the ABDI system a fuel pressure regulator adjusts the fuel pressure to ride approximately 70 kPa above the air pressure (which is at approximately 480 kPa). In the CPDI systems the fuel pressure is set to a fixed pressure of 550 kPa, but the mixing cavity pressure depends, as we have seen, on the blast valve timings. The actual amount of fuel delivered is inversely related with the pressure differential between the fuel and the air rail or mixing cavity. It is likely that at higher loads the mixing cavity pressure is rising high enough to inhibit proper fuel delivery, and therefore running slightly leaner than expected.

EMISSIONS REDUCTION COMPARISON

Given an ECU capable of operating the CPDI system in the either the singly, or doubly actuated mode, it could chose which mode was most advantageous at each operating point. If we compare the average emissions of the carbureted, and air blast DI system to the better of the CPDI systems we get the data of figure 21.

	HC (ppm)	CO (%)	NO_X (ppm)
Carbureted	3984	6.3	218
ABDI	470	3.2	471
CPDI	548	1.0	804

FIGURE 21 Averaged emissions comparisons for the various techniques. CPDI numbers correspond to the better of the CPDI-1 or CPDI-2 techniques for each point.

Compared to the carbureted engine, the ABDI system reduced HC emissions by about 88%, and CO emissions by 49% while NO_X emissions were roughly double that of the carbureted system. The CPDI technique reduced HC by 86% and CO by 83% while nearly tripling the NO_X emissions compared to the carbureted system. As the HC are calibrated to hexane, the actual number of carbon atoms in the DI system's exhaust is still approximately three times that of the NO_X. Therefore the increase in NO_X is not regarded as a problem, given the significant reductions in HC with the DI techniques.

CONCLUSIONS

Our goal was to demonstrate a less intrusive alternative to the air blast direct fuel injection system for retrofit application to small-displacement, carbureted, two-stroke engines. A compression pressurized direct fuel injection system was designed which eliminates the air pump of the ABDI system in favor of using compression pressurization for the "blasting" of the fuel into the combustion chamber. The CPDI system was tested for power and emissions, and these results were compared to those of the original carbureted system and the air blast DI system. Both of the DI techniques greatly reduce the emissions of hydrocarbons (88% for ABDI and 86% for CPDI) compared to the carbureted engine. CO emissions were also reduced (49% for ABDI and 83% for CPDI), while NO_X emissions were roughly doubles for the ABDI system, and nearly tripled for the CPDI system. The lower CO and higher NO_X emissions of the CPDI system are believed to be due to operating leaner than the ABDI system. Based on these results it appears that the CPDI system may have promise as a less-expensive and less-intrusive alternative to the ABDI system as a retrofit option for small two stroke engines.

FUTURE WORK

Further work in this area should focus on proper regulation of the fuel pressure to eliminate the lean tendency of the CPDI system. Additionally, there is need of an ECU capable of operating the CPDI system in the single and dual blast mode, with wider timings than available on the current ECU. Finally extensive field trials will be necessary for further system refinement before the CPDI technique is ready for mass deployment.

ACKNOWLEDGMENTS

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CONTACT

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ABBREVIATIONS

ABDI: Air Blast Direct Fuel Injection

CO: Carbon monoxide

CO_2: Carbon Dioxide

CPDI: Compression Pressurized Direct Fuel Injection

CPDI-1: Single actuation CPDI

CPDI-2: Double actuation CPDI

CSU: Colorado State University

DI: Direct Fuel Injection

ECU: Electronic Control Unit

EECL: Engines and Energy Conversion Laboratory

EOB: End Of Blast

EOR: End Of Recharge

HC: Hydrocarbons

N_2: Nitrogen

O_2: Oxygen

SOB: Start Of Blast

SOR: Start Of Recharge

WOT: Wide Open Throttle