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A Novel Low Cost High Frequency Fuel Injection System for Small Engines

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ABSTRACT

Small engines (<19kW) are used in many off-road applications, in both the domestic and industrial markets. The dominant driving force in these markets is cost; therefore the vast majority of these engines still use low cost carburettors to meter the fuel into the intake port. However all these engines are now facing increasingly strict emission targets and hence require new technologies to meet these new regulations, but any new technology must be extremely cost effective to be applicable.

The conventional fuel injection solutions used for many years in the automotive market require complex systems including a fuel pump, pressure regulator, and fuel injector coupled to a sophisticated control module and a multitude of sensors. This type of solution is far too complex and expensive for the vast majority of engines in the small engines market, and would cost significantly more than the engine itself.

A novel solution to this problem is high-frequency Pulse Count Injection (PCI). This design of fuel injection system has a single injector, shown in figure 1, which works as a simple positive displacement pump with a fixed geometric volume (typically 0.5μL). Each time the injector is energized it will deliver this known quantity of fuel to the engine (Fig. 2,) without the need for a separate fuel pump or regulator. The total amount of fuel required by the engine can therefore be delivered as a number of high frequency pulses each engine cycle.

With the pulse injector working at a fixed frequency (over 1kHz) and a fixed pulse width, the fuel requirement for the complete speed/load range of a small displacement engine can be accomplished.

Load and speed inputs can be processed very simply, and as a result the electronics and the power required to run such a system can be kept to a minimum.

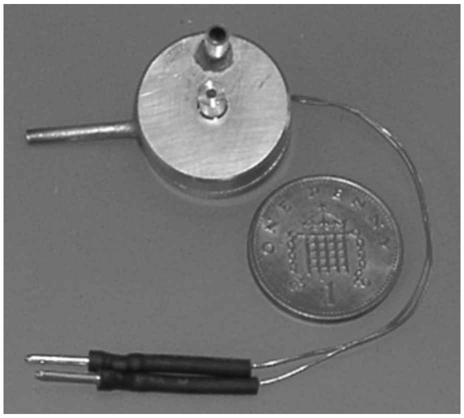


Figure 1. A PCI next to a UK penny (20mm diameter).

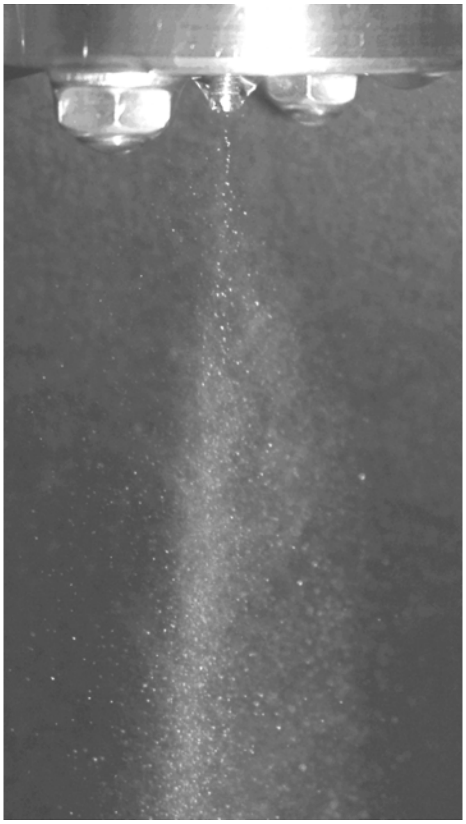


Figure 2. Spray pattern generated by a prototype PCI

1. INTRODUCTION

New emissions legislation for small engines are coming into force world-wide [Ref]. This will affect all small engines under 19kW in power.

In many applications manufacturers have already switched from 2-stroke to 4-stroke engines to achieve cleaner emissions, and manufacturers of 4-stroke engines are expecting to add catalytic converters in the near future. [Ref [1] EPA document]

However, this market is extremely cost sensitive with many of the engines being single cylinder, air-cooled, small capacity units using simple carburettors. It is therefore vital that any technology added to the engines must achieve maximum emission benefit for absolute minimum on-cost and minimum parasitic power consumption.

A limited number of options are available to meet these emission standards; they include continued use of carburettors with the addition of a 2-way catalyst or electronic fuel injection fitted with or with-out a catalyst.

Whilst it is generally accepted that the electronic fuel injection technology is the best way to achieve accurate fuel flow control under all conditions (as demonstrated by its use in the automotive market) it is also recognised that a typical automotive fuel injection system, including injector, pump, pressure regulator, sensors and a substantial electronic controller, is too complex and expensive for application into the market.

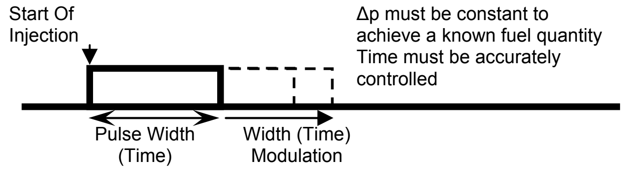
Therefore this paper presents the first step towards making a novel low cost high frequency fuel injection system that is specifically designed for the small engine market.

1.1 Pulse Width Modulation (PWM):

The conventional approach to fuel injection is to control the quantity of fuel injected per engine cycle by PWM, as described in Figs.3 and 4. With this process the fuel quantity delivered is controlled by a known fluid flow rate through a fixed orifice over an accurately controlled time period, as shown schematically in Fig. 3.

To control the fluid flow rate accurately it is necessary to control the pressure difference across the outlet orifice precisely. This is usually achieved by the combination of a high pressure fuel pump and a pressure regulator with a pressure compensation feed connected to the intake plenum of the engine.

Along with these pressure system components it is also necessary to have an on/off flow control valve (injector) that will open and close very rapidly with high repeatability matched to a very sophisticated electronic controller allowing for precisely controlled opening periods of the flow valve.



Fuel quantity delivered = Δp x time

Figure 3. Schematic of a PWM injection process for a single engine cycle.

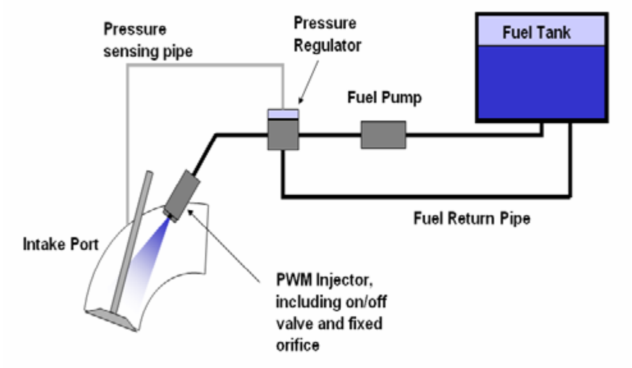


Figure 4. Illustration of components in a PWM fuel system.

The application of this system to small engines requires an exercise in miniaturisation. This has been achieved by some manufacturers already and their products have been released into the market. [Ref: 2,3] (Keihin, Mikhuni.)

The PWM system in its present form is inherently cumbersome when applied to a small engine and its parasitic losses could prove too great to overcome.

The cost of PWM with its separated components, high pressure pipe work, wire looms and expensive sensors could limit its use. The part count for such a system and the weight added to the product is also a restriction to its application in this market.

1.2 Pulse Count Injection (PCI):

As an alternative to PWM the novel concept of PCI [Ref. 4] has been developed to deliver the precisely controlled fuel quantities required per engine cycle.

PCI uses a small geometrically fixed volume to repeatedly inject a known amount of fuel into the engine intake manifold.

The number of pulses of injected fuel per engine cycle determines the amount of fuel delivered to the engine, as shown schematically in Fig. 5.

In order to achieve this fuel flow control process the PCI injector is constructed as a simple positive displacement pump with a solenoid driven piston working in a cylinder as the fixed volume displacement unit. Two one-way check valves (a fuel Inlet valve and fuel outlet valve.) ensure the correct flow path of the fluid into and out of the injector.

In this arrangement the single PCI injector acts both as the pumping unit and the flow metering unit together.

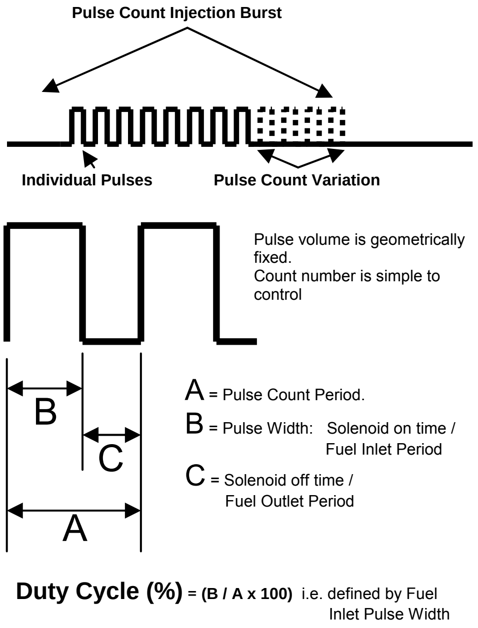


Figure 5. Schematic of a PCI process for a single cylinder cycle.

The flow volume delivered by each pulse is a fixed geometric volume and it is supplied at a fixed frequency and pulse width.

The PCI fuel delivery method, therefore, is independent of differential pressure across the injector, making it very insensitive to pressure fluctuations in the intake manifold.

The PCI system, shown in Fig.6, contains significantly fewer parts than the PWM system but still delivers an accurately controlled volume of fuel to the engine each cycle.

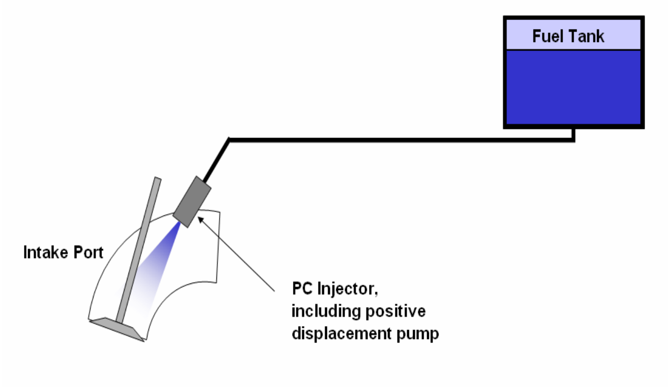


Figure 6. Illustration of components in a PCI fuel system.

The total system part count for the PCI is inherently low and all of the components are packaged together in a single small unit, this leads to possible cost savings over a standard Injection system. These features also increase its robustness and serviceability.

A typical fixed volume is approximately 0.5μL, with a typical operational frequency of greater than 1kHz. This range is suitable for many engine capacities in the small engine market.

2. INTERCHANGEABILITY.

One of the key design features of a PCI injector is that one unit (e.g. using the same piston bore and stroke) is interchangeable with different engine sizes and engine applications. Additionally by having just a few alternative piston diameters and strokes it is possible to cover the whole range of engine sizes available in the market. This leads to a drastic reduction in the size of the ‘Bill Of Materials’ (BOM) requirements for a production run compared to the large numbers of different carburettors required to cover the same number of engine derivations.

To choose the correct PCI for a particular engine application the fuel flow Turndown Ratio (TDR) must be derived.

The TDR is the ratio between the maximum fuel flow (usually taken at maximum load and maximum RPM) and the minimum fuel flow value (no load/min rpm)

In an automotive situation the turn down ratio can be as large as 100:1 but for the small engines market a typical maximum of 9:1 to a minimum of 6:1 is normal and covers most applications due to the nature of operation of these engines.

A bench marking exercise was undertaken covering engines from 50cc up to 430cc in size to verify the required TDR’s; an example of which is shown in Table 1. below.

Table 1. Example of TDR data of a PCI running at 1kHz for an engine of 80cc displacement.

Eng. Speed (Rpm)	Load (Watts)	Fuel Cons. (L/hr)	PCI Volume (μL)	No. of Fuel Pulses (/ Cycle)	Max No. of Fuel Pulses (/ Cycle)	TDR
1300	0	0.11	0.24	12	92	6.3
3050	1000	0.69	0.24	31	39	1

An injector sizing database that defines the number of different PCI configurations required to cover engine sizes from 50cc up to 450cc was constructed in this fashion.

The different PCI configurations are determined by piston diameter and stroke.

The database results have been represented in Fig. 7 shown below.

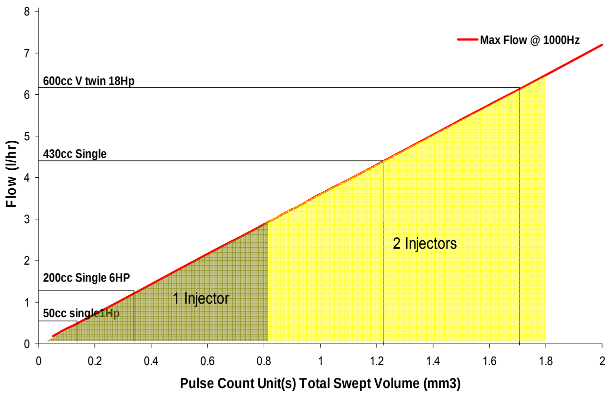


Figure 7, Fuel flow rate v's PCI displacement volume for different engines based on 1kHz injector operation with the engines running at full load.

As can be seen in Fig. 7 for engine sizes that require a pulse volume greater than 0.8μLtrs the use of two 1kHz injectors is sufficient to deliver the required fuel flow.

3. FIRST HARDWARE CONCEPTS

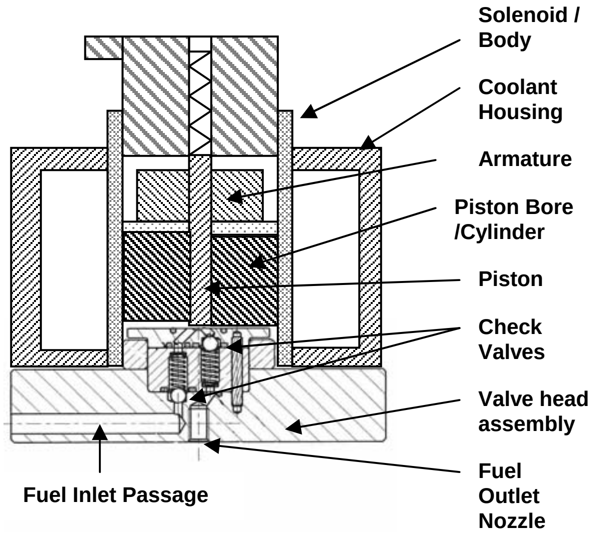


Figure 8. A sectioned drawing of the prototype Pulse Count injector.

The first prototype version of the PCI concept was constructed from “off the shelve components”.

For example the solenoid and armature assembly are sourced from a standard Gasoline Direct Injector with a special valve head assembly fitted below it. See schematic shown in Fig. 8.

Once the prototype PCI had been built it was tested on the spray bench, the durability rig and the engine test rig.

4. SPRAY BENCH TESTING

The Injector Spray Rig, shown schematically in Fig. 9, consisted of the following Parts: Fuel tank, xy traverse and stand, Pulse Count Injector, Coolant system, catch tank, mass-balance, Pulse Generator and Transistor Amplifier. (The xy traverse allows alignment of the injector with the fuel catch tank.)

The fuel used was pump Gasoline (95RON.) at 25degC

To drive the PCI a standard NPN transistor (TP 121) was used as the signal amplifier, switching the solenoid to earth.

The power supply used was a standard RS Laboratory unit rated to 30A. The voltage for all these tests was held at 13.8V.

The signal generator used was a DEI PDG-2510. This has a burst function enabling a set number of pulses to be fired at set intervals. The interval function was set to 2Hz and the number of pulse counts to 100.

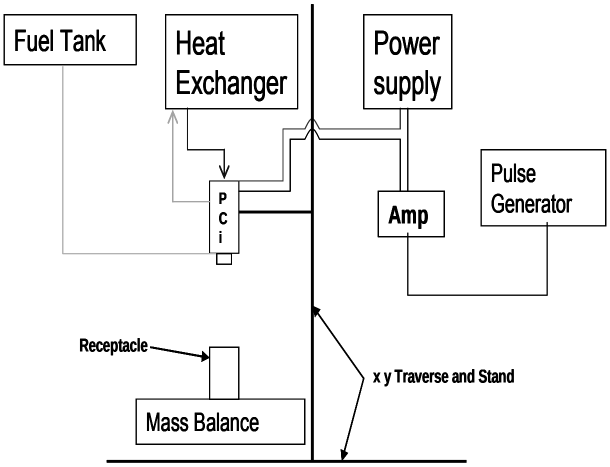


Figure 9. Schematic of the PCI spray rig.

The Mass of Fuel per Pulse was used as a performance marker and the variables in all of the experiments were:

- Frequency
- Duty Cycle (Based on the solenoid on time to off time.)

The aim of the experiment was to map the injector performance at different frequencies and pulse widths. Therefore enabling a running condition to be found that gave a mass / pulse condition good enough to allow stable engine running.

4.1 Results

Shown in Figs. 10 and 11 are the results of an optimised prototype PCI running from 300Hz to 1kHz. Fig. 10 shows the mass/pulse performance of the PCI for each frequency with the duty cycle set to give maximum fuel delivery.

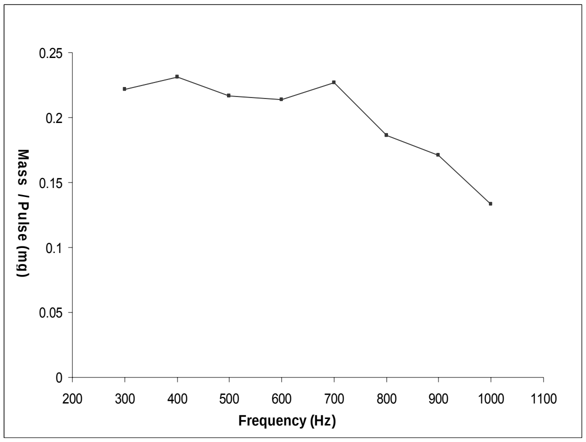


Figure 10. Maximum Mass / Pulse of fuel vs. Pulse Frequency for prototype PCI.

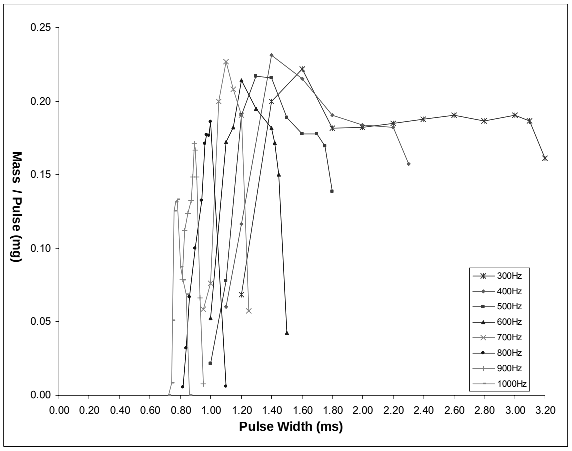


Figure 11. Mass / Pulse vs. Inlet Valve Pulse Width for the Prototype PCI.

Fig. 11 shows the full data set with the inlet pulse width on the horizontal axis as the duty cycle was varied at each set frequency.

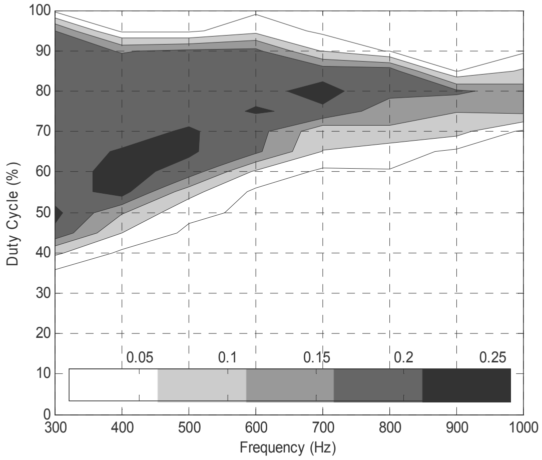


Figure 12. Duty Cycle vs. Frequency for the modified PCI, with contour lines of common Mass of fuel / Pulse delivered (mg).

It can be seen that the prototype PCI does not respond at any frequency until an inlet pulse width (time B shown in Fig. 5) of approximately 0.8ms has been achieved. This is attributed to the large inductance of the solenoid and the relatively large mass of the piston/armature.

Fig. 12 shows the injectors overall spray performance.

The upper set of decreasing contour lines describe the performance boundary of the outlet valve, its performance is affected by the amount of time it has been given to open. This is a function of solenoid 'off' time (time C shown in Fig. 5) and is controlled by the duty cycle of the pulse frequency.

The lower set of decreasing contour lines describe the performance boundary of the inlet valve, again its performance is affected by the amount of time it has been given to open. This is a function of solenoid 'on' time (time B shown in Fig. 5) and again is controlled by the duty cycle of the pulse frequency.

The narrowing 'wedge' of common mass per pulse in-between the contour lines shows a large tolerance to varying duty cycle settings at low frequencies and a narrowing of that tolerance band at the higher frequencies.

This can be attributed to the total system response time including the influence of the fluid flow through the check valves and orifices, the mass of the piston/armature, the force of the return spring, the inductive force of the solenoid and the armature latching created by back EMF.

The following photograph, Fig 13, was taken on the spray bench using a digital camera with flash. It shows a series of pulses of fuel from a prototype PCI running at 1kHz, the volume of fuel per pulse in this running condition = 0.14µL.

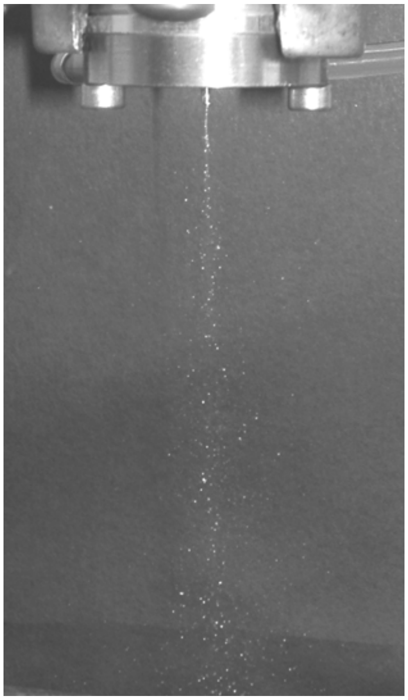


Figure 13. Spray from PCI operating at 1kHz.

5. INJECTOR DURABILITY RIG TESTING

The PCI was set up in the test stand shown in Fig 14. The objective of the durability testing was to run the PCI on an accelerated wear program at a fixed pulse rate in order to cycle the moving parts rapidly through the equivalent number of cycles as a complete engine life.

The settings used were:

- Pulse delivery volume = 0.44 μL
- Pulse Frequency = 500Hz
- Inlet Pulse Width = 1.4ms
- Pulse burst number = 100
- Interval time = 500ms

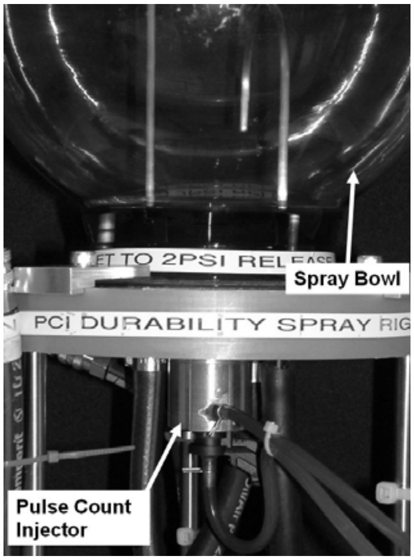


Figure 14. PCI Durability test rig.

The PCI running in the durability test rig completed over 100hrs operation (100hrs = 52million cycles) with no signs of significant wear.

6. ENGINE RIG TESTING.

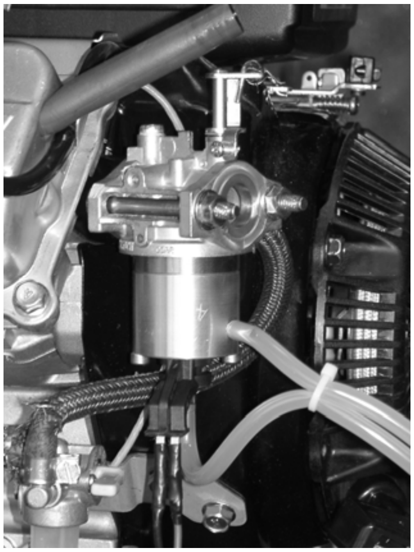


Figure 15. Prototype PCI fitted to the throttle body of an 80cc engine.

As shown in Fig. 15 the prototype PCI was fitted to a cut down carburettor body to act as a throttle body with the original central main jet being used as the outlet orifice for the fuel.

The standard fuel tank, filter and pipe work were used and the standard engine throttle governor remained connected to provide load control

The control system used consisted of two pulse generators (Thurlby Thandar TGP110 10MHz.) These were used to operate two TP121 transistors which were linked such that one was constantly providing a signal at the required pulse frequency and pulse width (the oscillator pulse generator) and the other controlled the 'window' of pulses going to the PCI injector by changing the output signal pulse width (the control pulse generator.) The control pulse generator was triggered by a cam signal taken from the top of the exhaust valve rocker using a 'Hall' effect proximity sensor. The delay to the pulse was manually controlled also by the control pulse generator.

The control pulse generator's pulse was altered manually to provide the correct fuelling, by changing the no of supplied pulses, at a specific load setting.

The PCI injector specification was as follows:

- Piston diameter = 2mm
- Piston stroke = 0.14mm
- Pulse delivery volume = 0.22 μLtrs
- Pulse frequency= 500Hz
- Pulse width = 1.4ms

The engine was run at 3000rpm (the speed set by the governor.) At no-load the engine required 8 pulses of fuel per cycle.

With this initial prototype PCI set to a fixed operational frequency of 500Hz the maximum number of pulses that could be injected per engine cycle, in this early iteration of the prototype, was 20. In this condition the maximum load that could be applied to the engine (via the generator) was 300W compared to the maximum 1kW as rated. Fig. 16 shows schematically the individual pulses relative to crankshaft position for different loads throughout the engine cycle.

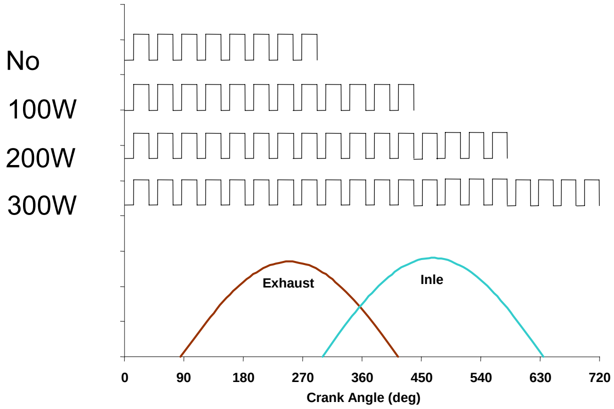


Figure 16. Is a graphical representation of a single engine cycle in degrees with the Valve opening times and the number of pulse for a particular load superimposed on to it delivered at 500Hz.

The engine was run with the PCI in this configuration successfully for over 25hrs to assess initial durability and stability of operation.

Subsequently the prototype injector was modified to increase the pulse frequency at which it could work at to 1KHz (the spray rig results presented earlier relate to this,) doubling the amount of pulses of fuel that could be supplied to the engine. Therefore the full load of 1kW could be applied to the generator set.

6.1 Engine Emission Testing

Following on from the engine test work some initial emission tests were performed on the 80cc engine fitted with the 1kHz PCI injector.

The emission tests were carried out in line with EPA Part 90.3 test procedures.

The emission analyser used was an Oliver IGD Tocsin 320. This is a six gas analyser (CO, O2, CO2, NO, NO2, HC.)

Before the engine emission tests were undertaken a ‘real time’ back to back calibration was performed on the analyser with a Horiba 7100 as the certified comparison using the same engine. This was carried out at the Motor Industry Research Association (MIRA) which is UK based.

Before each of the test runs span gas was used to calibrate the unit.

Comparisons of the PCI injector with the standard carburettor were made and are shown on the graph in Fig. 17. The tests were performed on the same engine with the same un-modified standard carburettor performed over the life of the engine (TS000 = test sheet number.)

The graph shows the result of optimising the PCI to achieve the best combined emission result.

Optimisation comprises of timing the injection event during the cycle and controlling the Air/Fuel Ratio at each specific emission test point, something that cannot be readily achieved with a standard carburettor.

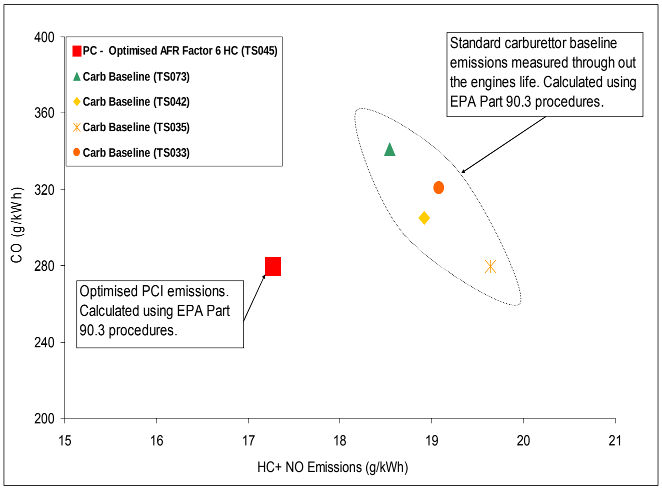


Figure 17. 80cc Engine Emission Test Results with comparison between the engine with a carburettor and PCI.

As can be seen in Fig. 17 a clear decrease in emissions can be achieved by optimising the AFR using a PCI when compared to the standard carburettor.

Further reductions in emissions can be achieved by optimising the fuel injection timing and fuel atomization.

7. FUTURE WORK

The integration of the PCI injector into a compact single unit encompassing all of the required electronics to run an engine is the focus of the development currently being undertaken.

Details of this work will be released in subsequent papers.

8. CONCLUSIONS

- As a fuel control system the PCI injector has proven itself on the spray bench and on initial engine tests as a viable alternative to either standard automotive style fuel injection or carburettors.
- Reduction in emissions by Pulse Count Injection fuel control alone has shown a lowering of emissions by 10% compared to the standard carburetted engine.
- The simple design and packaging of the PCI injector and the low processing power required to run small engines could possibly lead to a low cost fuel injection system.

REFERENCES

[1] EPA Final Regulatory Impact Analysis Document; EPA420-R-99-003. March 1999.

[2] Development of Compact and High Performance Fuel Injector using Electromagnetic Field Simulation, H.Watanabe et. al. SETC 2005. Paper 20056535, 2005-32-0019, Bangkok 12-14 October 2005.

[3] Development of a Discharge Pump Type Fuel Injection System for Small Two-Wheeled Vehicle, T.Karasawa, S.Hasimoto, R.Ehara, SETC 2005. Paper 20056536, 2005-32-0022, Bangkok 12-14 October 2005.

[4] Flow and Spray Characteristics of a High Frequency Low Cost Fuel Injection System for Small Engines. J.Allen, P.Ravenhill, ICLASS-2006. Paper ICLASS2006-243, Kyoto, Japan, Aug 27-Sept 1, 2006.

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