

Experimental Results of New Fuelling Strategies for High Frequency Low Cost Injection Systems for Small Engines

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ABSTRACT

With increasing pressures to reduce engine emissions in the small engines market there is a need to precisely meter the fuel flow into the engine under all running conditions. Therefore this cost competitive market requires a well engineered injection system that combines good control of fuel metering at all speed / load conditions, and meets the markets competitive pricing requirements. It must also offer the potential to allow these engines to meet stringent future legislation, leading to the addition of closed loop control with 3 way catalysts.

This paper presents an experimental investigation into the effect of wall wetting and fuel injection strategy on a small engine. The engine was fitted with a novel form of port fuel injection, Pulse Count Injection (PCI) [1.] This novel high frequency digital fuelling system allows rapid oscillation of the fuel quantity from one engine cycle to the next.

The result of the investigation is a novel fuelling strategy that enables good fuelling control under no load idle conditions where very fine fuelling control is most desired.

INTRODUCTION

Small (<25kW) spark ignition (SI) engines used in many applications, from low cost motorcycles, generators, water pumps, to lawn and garden equipment, are facing stricter emission regulations on a world wide basis [1]. To address these current and future regulations there is a need to precisely meter the fuel flow into the engine under all running conditions. However the nature of the small engine market sector is that any fuel injection system must be very low cost.

All fuel control equipment, including electronic carburettors and fuel injection systems, must achieve the required resolution to optimise the air-fuel ratio (AFR) under all operating conditions. The most critical resolution issue will occur at the lowest fuel flow condition of no-load idle. Under these conditions the engine sees its lowest air and fuel flow rates and a small fuelling change will have a significant effect on the AFR each engine cycle.

Wall wetting in the intake port also affects cyclical AFR resolution. This is common to all carburetted or port injected engines and it is evident from this that not all of the fuel metered into the intake port on a specific engine cycle will reach the combustion chamber. In fact fuel deposited on the walls of the intake port has some residency time (number of engine cycles) before being induced into the combustion chamber.

It is therefore important to understand the amount of port wall wetting present and the fuelling resolution required by typical small engines to achieve an adequate control of AFR. Excessive wall wetting could make very fine levels of fuelling resolution of little benefit to engine in terms of its stability and engine out emissions.

Pulse Count Injection is a novel high frequency fuel injection system [1 & 2]. PCI delivers the total fuel required by the engine each engine cycle in a number of fixed volume pulses. This paper describes a series of engine based experiments carried out to explore the issue of fuel wall wetting and refinement at engine idle condition.

TEST EQUIPMENT & OBJECTIVES

The test engine used for these sets of experiments was a 6.5hp single cylinder, with a vertical crankshaft, shown in figure 1. Details are as follows:-

- 4 stroke – air cooled
- Capacity 190cc
- OHV Single cylinder
- Vertical shaft
- Governed idle 2000rpm

The inlet port lengths used during the test were:-
(Engine inlet valve to throttle body dimension)

- Short = 75mm
- Medium = 117mm
- Long = 159mm

The injection System details were:-

- Pulse Count Injection
- 600Hz operating frequency
- Pulse volume 0.8µltrs/per pulse
- Number of pulses per engine cycle – variable 1 to 36

Emissions analyser used:-

- Oliver IGD Tocsin 320, 6 gas analyser

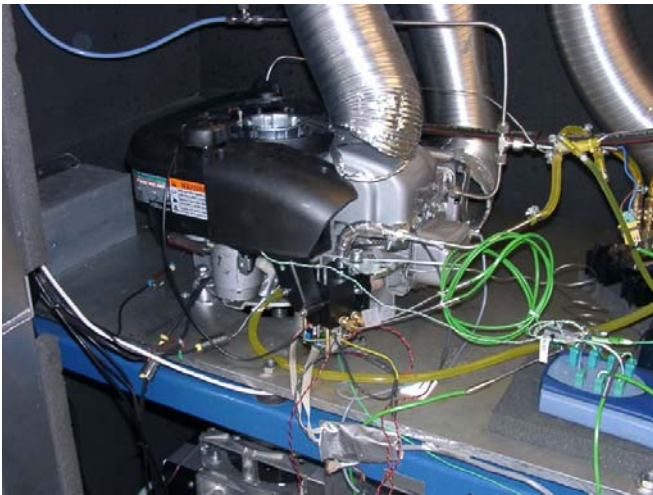


Figure 1. 6.5 Hp Test Engine Installation

The Pulse Count Injection fuelling system used is a low pressure, high frequency, digital fuel injection system. Each time the injector is energised a fixed small quantity of fuel is injected. The quantity of fuel is geometrically fixed by the internal dimensions of the injector [2].

The desired fuel flow is set by controlling the number of times the injector is energised (pulsed) per engine cycle. The design of the injector atomization system is such that fuel is ejected into the intake-port only during the engines induction stroke, and therefore the process can be considered an open inlet-valve injection system. This injection system is electronically controlled allowing accurate and controllable fuel quantities to be delivered each engine cycle.

To investigate the sensitivity of engine stability to cyclic fuelling changes, accurate variations of fuelling from cycle to cycle can be made, enabling simple test procedures to be used.

The first objective was to investigate inlet port fuel wall wetting, for which a ‘transient fuelling test’ was developed.

The aim was to understanding the quantity and nature of what is in effect a transient fuel reservoir.

The second objective was to understand the acceptable limits of AFR variation the engine could cope with cycle to cycle. To achieve this, the ‘switching test’ was developed where the average fuelling was kept constant, but the individual cycle fuelling was alternated either side of the average.

AFR resolution was further tested by fuelling the engine in groups of eight cycles. The number of pulses per cycle would be set to, for example, 4, 5, 5, 5, 5, 5, 5, 5 e.g. a fuelling equivalent to 4 and 7/8ths of a pulse if an average of the eight cycles is taken. The fuelling was then altered by the addition or subtraction of pulses across the 8 cycles.

Further work included the fitting of 3 different inlet runner lengths changing the wall wetting fuel residency time and the effective fuel reservoir volume.

TEST METHOD

1) Transient Fuelling Test

This test was aimed at understanding the usable quantity of the fuel resident in the inlet runner. The test engine was run at idle with a fixed number (= 5) of fuel pulses per cycle. The governed idle speed for the test engine was 2000rpm. For this test the throttle position was fixed. This fuelling equated to a Spindt AFR of 11.5:1. Engine revolution time and steady state emissions logging was started. The number of fuel pulses per cycle was then dropped to 4 pulses per cycle, whilst continuing to log the test data. 4 Pulses per cycle equated to a steady state Spindt AFR of 14.4:1. At a steady state, 4 pulses per cycle fuelling, the test engine stability was poor resulting in a drop in engine speed. By examining the engine speed, from the engine revolution time in the period following the switching from 5 to 4 cycles an assessment could be made of the usable quantity of fuel resident in the port.

2) Switching Test

The test engine was run at the same 2000rpm, no load idle point and 5 pulses per cycle as the previous test. The steady state emissions and engine revolution time were logged. The fuelling was then modified to give a cycle by cycle sequence of pulses of 4, 6, 4, 6 etc. The average fuelling was the same, but each cycle had fuelling with a 20% variation from the mean.

Subsequent tests were undertaken with a cycle by cycle sequence of 3, 7, 3, 7 (40% variation from the mean), then 2, 8, 2, 8 etc. (60% variation from the mean) and finally where possible 1, 9, 1, 9 etc. (80% variation from the mean).

3) AFR Resolution Test

Again the test engine was fuelled at a continuous 5 pulses per cycle, 2000rpm no load and the test data logged. This fuelling equates to 40 pulses over 8 cycles. The fuelling was then modified to gradually reduce the fuelling level by 1 pulse in 8 engine cycles, but still running the engine in a continuous 8 cycle loop. Therefore to achieve 39 pulses per 8 cycle group, the following pulses per cycle were used, 4, 5, 5, 5, 5, 5, 5, 5 (an average of 4 and 7/8th pulses per engine cycle).

Further tests were run with the pulses per 8 cycle group reduced 1 at a time in the sequence shown in figure 2.

Pulses per Individual Cycle Based on a Group of 8 Cycles

Pulses / 8 Cycles	Individual Cycle no.							
	1	2	3	4	5	6	7	8
40	5	5	5	5	5	5	5	5
39	4	5	5	5	5	5	5	5
38	4	5	5	5	4	5	5	5
37	4	5	5	4	5	4	5	5
36	4	5	4	5	4	5	4	5
35	4	4	5	4	4	5	4	5
34	4	4	4	5	4	4	4	5
33	4	4	4	4	4	4	4	5
32	4	4	4	4	4	4	4	4

Figure 2. Individual cycle fuelling to give effective 1/8th pulse resolution

RESULTS & DISCUSSION

Figure 3 shows the results from the transient fuelling test, with the engine speed traces from the 3 different inlet runner lengths. The x axis is engine revolutions. As the fuelling is switched from 5 to 4 pulses per engine cycle, the calculated engine speed per revolution can be seen. The saw tooth plot shows the firing and non firing portions of the cycle from this single cylinder engine.

For each cycle that the engine speed is maintained, following the drop from 5 to 4 pulses per cycle, a quantity of fuel approximately equal to one pulse is being successfully drawn from the port fuel 'reservoir' to replace the reduced fuelling from the injector.

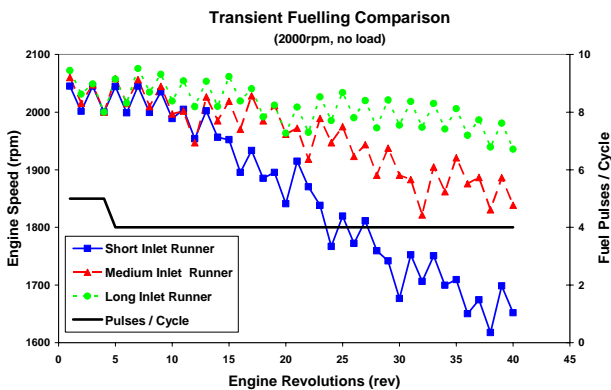


Figure 3. Transient Fuelling Test Results

The short inlet runner trace (shown in blue), shows 1 clear cycle without a speed drop. The starting point being taken from the last induction stroke (low speed portion of the engine cycle) at revolution number 4 and subsequent firing (high speed portion of the engine cycle) at revolution number 5. Following the speed trace on, it shows 1 clear cycle without a speed drop up to revolutions 6 & 7. The next full engine cycle, revolutions 8 & 9, starts to show the first sign of the overall engine speed tailing away.

The medium length intake port (shown in red) also shows the first signs of reduced speed at the same revolution number after the injector flow has been reduced from 5 to 4 pulses per cycle, but the overall slowing trend is not as fast as with the short port, indicating that there is a greater total volume of fuel on the wall surface acting as a reservoir volume.

Finally the long port length (shown in green), which has the greatest surface area for wall wetting, shows a greater degree of instability but only sees a real reduction of engine speed after revolution number 15, some 10 revolutions after the fuelling level was reduced, and the slowest overall speed reduction rate of the 3 port lengths tested.

Whilst there will be variation cycle to cycle even under steady state conditions it can be stated that the longer the inlet runner the slower the fall away in engine speed.

In terms of fuel quantity present due to wall wetting in the inlet port, only 2 pulse volumes of fuelling could be reasonably relied upon without incurring a possible weakening of fuelling and the associated engine instability.

The nature of utility engine design means there is more likely to be a greater quantity of fuel resident in the inlet port, in proportion to its size, compared to a higher performance road engine. However even road engines have wetting of the inlet walls, (a percentage of fuel is issued from the injector outside the quoted cone angle) and fuel is invariably injected into the inlet port with a closed inlet valve, with inevitable fuel wetting of the port locally.

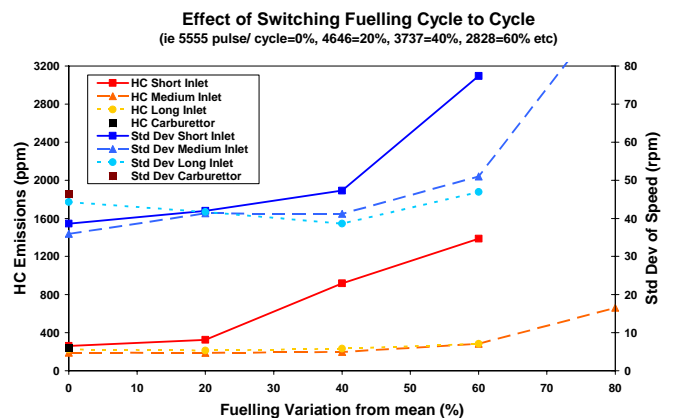


Figure 4. Switching Test Result

The switching test (figure 4) examined the extent to which the fuelling could be oscillated, cycle to cycle, before the stability and subsequent emissions suffered. All of these tests were carried out with the same average fuelling rate (5 pulses per cycle) but with a varying degree of oscillation around the fixed average. The results from this test have a significant input on determining the boundary of the minimum number of pulses per cycle that will be acceptable without emissions or stability penalties.

With a short inlet runner (solid line) a 20% variation in fuelling cycle to cycle was the limit. By 40% the HC emissions and stability (measured in terms of standard deviation of speed) had risen.

Using this acceptable fuelling variation cycle to cycle of 20%, and adding the idea of linking 8 cycles together will be shown later, to give a limit to the minimum number of pulses acceptable to approximately 4 whilst maintaining an acceptable fuelling resolution.

The medium inlet port (dashed line) gave an increased tolerance to cycle to cycle fuelling variation. The first transient test (figure 3) had shown that with the medium runner, 2 pulses of fuelling could be supplied from the inlet port wall. The switching test (figure 4) shows also the medium runner can cope with a 2 pulse deficiency on one cycle when the subsequent cycle has 2 pulses extra compared to the average value to replenish the wall wetting reservoir.

The long inlet port (dotted line) showed very similar trends to the medium port, indicating that although there was a greater quantity of fuel available from the larger wall area (shown in figure 3) there is a transportation and response time function of how rapidly the fuel can be delivered into the combustion cylinder.

AFR resolution test results are shown in figure 5. This shows that by grouping 8 cycles together, as described in figure 2, the resolution of the fuelling control using the effect of a fuel reservoir caused by wall wetting is improved. Stable engine running was achieved from the 5 pulses per cycle (11.5:1 AFR) down to an effective 4.25 pulses per cycle (13.7:1 AFR).

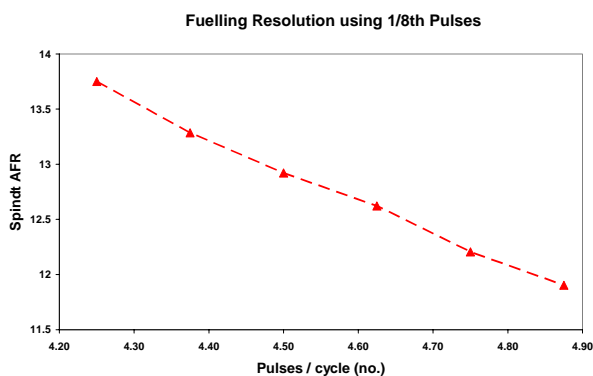


Figure 5. Fuelling resolution using 8 cycle grouping

The switching test had shown an acceptable variation in fuelling from one cycle to the average fuelling of up to approximately 20%. Figure 6 takes the 8 cycle group sequences shown in figure 2 and displays the variation in fuelling of the individual cycle furthest from the 8 cycle average.

For example, if the fuelling for an engine required 3 and 7/8th pulses per cycle (i.e. 31 pulses over 8 cycles), the pulse per cycle over the group of 8 cycles would be:-

3, 4, 4, 4, 4, 4, 4, 4

The group average is 3.875.

The variation of the first, furthest from average cycle, is:-

$$(0.875/3.875) \times 100 = 22.6\%$$

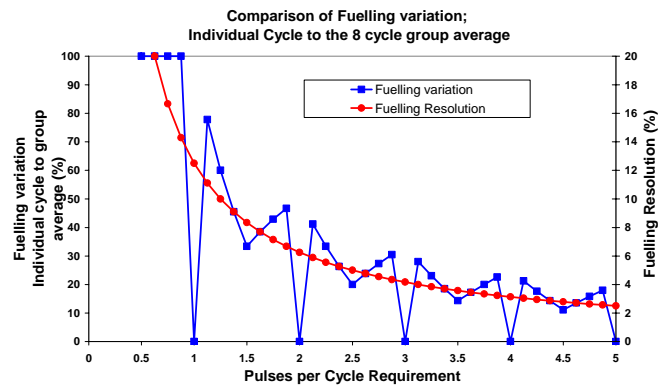


Figure 6. Theoretical plot of fuelling variation

From this plot an acceptable minimum number of pulses per cycle can be determined

If 20% variation in fuelling cycle to cycle is a target then the minimum number of pulses needs to be around 4.

As far as instability is concerned, figure 6 may be misleading, the probable worst conditions are the 1/8th pulse per cycle below an integer number, at this condition there is 1 weak cycle per group of 8. At the other extreme, 1/8th pulse per cycle over an integer figure there is 1 rich cycle. The tendency to poor combustion is greater with the former, than the later.

As well as the variation from cycle to cycle the total number of cycles an averaging process is run for will have an impact on final resolution. This is the need for a reasonable fuelling resolution, at 4 pulses per cycle using 8 cycle grouping this is just over 3%, i.e. fuelling at worst case can be set with 1.5% of the perfect figure.

CONCLUSIONS

1. On the small engine tested, which is typical of many engines in this market, a significant fuel reservoir is available in the inlet port of the running engine due to wall wetting. For the test engine this is equal to approximately 2/5ths of a one engine cycle fuelling.
2. The presence of the fuel reservoir allows cycle to cycle fuelling variations of up to 20% to be tolerated without stability or HC emissions penalty.
3. Longer inlet runners are more tolerant to fuelling variations cycle to cycle because they are larger volume fuel reservoirs.
4. By grouping 8 engine cycles together, and oscillating the fuel delivered from cycle to cycle an effective 1/8th pulse resolution can be practically achieved.
5. A minimum of 4 pulses per engine cycle gives acceptable resolution of fuelling combined and acceptable stability can be achieved.
6. A low cost fuel injection system with lower absolute fuelling resolution can be successfully used to control an engine fuelling with acceptable resolution by using an 8 cycle averaging strategy.

REFERENCES

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