

Investigating the Effects of Multiple Pilot Injections on Stability at Cold Idle for a DI Diesel Engine

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ABSTRACT

An experimental investigation of combustion cycle-by-cycle stability under cold idling conditions has been carried out on a DI diesel to examine the influence of pilot fuel injection strategy. The engine is a single cylinder variant of a multi-cylinder design meeting Euro 4 emissions requirements. The engine build had a swept volume of 500cc and a compression ratio of 18.4:1. Work output and heat release characteristics have been investigated at test temperatures of 10, 0, -10 and -20°C and speeds in the range from 600 to 1400rpm. At the lowest temperature, -20°C, stability is sensitive to the timing of main injection and is prone to deteriorate with increasing engine speed. The influence of the number of pilot injections and pilot fuel quantity on stability has been explored. Best stability was achieved by increasing the number of pilot injections as temperature is lowered, from one at 10°C to two at -10°C and between two and four at -20°C. At the lowest temperature, triple or quadruple pilot injections can broaden the region of stable operation across a range of injection timings and engine speeds. Heat release analysis shows that there is less cycle by cycle variation in phasing and cumulative heat release when multiple pilots are used.

INTRODUCTION

The cold start performance of diesel engines is prone to deteriorate as ambient temperature is reduced. The injection of a small quantity of fuel before the main injection can limit the deterioration by reducing the

number of misfiring cycles and promoting high work output. Previous work [1] has shown this pilot injection has an important beneficial effect on start up behaviour, but that post-start idling quality might still be poor. Improving cold idling using multiple pilot injection strategies has been the focus of the study reported here. Han et al. [2] correlated poor startability with misfiring cycles and developed a new strategy for diesel engine cold start down to -10°C to minimise misfire. Zahdeh et al. [3] also noted increasingly problematic skipped cycle operation when reducing ambient temperature to these levels. Cheng et al. [4] linked poor startability in an engine with high levels of blowby and were able to improve idle quality and long start times with the implementation of a new piston ring pack. Liu et al. [5] developed a model of the cold starting process which correlated well with experimental results in predicting multiple misfiring cycles at low temperatures due to high blowby and heat transfer as well as rapidly varying engine speeds.

The investigation of combustion stability, work output and heat release characteristics has been carried out at selected idling speeds between 600 and 1500 rpm on a single cylinder HPCR DI diesel. Test temperature was varied between 10°C and -20°C; most of the results presented are for the -20°C. Main injection timing was between 16°BTDC and TDC and up to 4 pilot injections were delivered in advance of the main. The average value and coefficient of variation of gross indicated work output over the first 25 fuelled cycles of a test were used as indicators of idling performance. The reasons for the trends observed in the results are described and their

The Engineering Meetings Board has approved this paper for publication. It has successfully completed SAE's peer review process under the supervision of the session organizer. This process requires a minimum of three (3) reviews by industry experts.

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ISSN 0148-7191

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9-2009-01-0612

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physical significance discussed. Effects on smoke and other pollutant emissions have not been examined. Although European regulations set limits on cold start HC and CO emissions at -7°C for gasoline [6], limits are not yet in force for diesel. The key concern in the current work has been the influence of injection strategy on cold idle stability.

EXPERIMENTAL SETUP

The experimental investigation has been carried out on a single cylinder version of a production Ford four cylinder, DI diesel which meets Euro 4 emissions requirements. The cylinder head, piston and crankshaft components were fitted in a Ricardo Hydra unit. The swept volume was nominally 500cc, bore and stroke both 86mm. The compression ratio was calculated to be 18.4:1. Diesel was supplied to the HPCR fuel injection system by a high pressure pump rated to 1350bar. Rail pressure at idle is generally much lower than the maximum, and was set at 400bar for all the tests after initial investigations showed no advantage was gained by running at a higher pressure. There was a centrally mounted 6 hole solenoid injector and four valves per cylinder.

The engine was soaked down to test temperature by circulating chilled coolant through the block, head and fuel tank. The principal method of cooling was the direct chilling of coolant by a 5.8kW cooler, capable of chilling to -30°C . An 80 litre plenum before the intake was also chilled using an atmospheric cooling radiator to provide a reservoir of low temperature intake air. The fuel used throughout these tests was a reference winter fuel to avoid paraffin waxing [Cetane Index >47 , T90 $<325^{\circ}\text{C}$]. Pressure transducers and thermocouples were used to monitor operation. Cylinder pressure was measured using a Kistler 6125B quartz pressure sensor rated to 250 bar peak pressure. An optical shaft encoder with half degree crank angle resolution outputs 720 DC pulses per engine revolution (1440 per cycle); this signal is the trigger for much of the dSPACE data acquisition system which captures system variables at each half crank angle step. ATI Vision was used to isolate the engine control unit and give full control over injection parameters.

The form of test used reflects the low speed, cold-surface conditions of start up with better control over variability. The glow plug was the same steel-sheathed design used in the production version of the engine; this has an operating surface temperature of around 850°C . Consistent with in-service operation and the known benefits of glow plugs as starting aids [7], the glow plug was switched on for a pre-heat period of 7.5 seconds and remained on throughout the test. The engine was motored for 15 cycles at the desired test speed, by which time both engine speed and fuel rail pressure had stabilised to their respective set point values. On cycle 16, fuel injection was enabled and injection quantities and timings were held constant for the following 25 cycles. The dynamometer was used to maintain the set point engine speed throughout the test.

EXPERIMENTAL RESULTS AND DISCUSSION

Various studies [1, 8-11] have concluded that cold start performance can be greatly assisted by the introduction of a pilot injection, promoting cool flame reactions creating an activated environment in which to inject the main. Previous work conducted by the authors [1] has confirmed this benefit at cold conditions during engine cranking and the run up to idle. Cold idle performance could still be poor, however, particularly at low loads and reduced temperatures. The aim of the work reported here was first to define the extent of the problem and then investigate the utility of different injection strategies to mitigate it. Although idle speed stability is a key indicator of idling quality for multi-cylinder engines, this depends on cycle by cycle combustion stability and the response of the speed control strategy. Here, these are decoupled using a motor-regenerator dynamometer to accelerate and hold engine speed at a target value for the test. This eliminates the need for the engine idle speed controller and allows fuel delivery to be fixed independently. Test results have been processed to determine IMEP_g (average gross indicated mean effective pressure over the first 10 injected cycles), StD_{IMEPg} (standard deviation of IMEP_g over the 25 injected cycles) and CoV_{IMEPg} (Coefficient of Variation of IMEP_g as a percentage). Cycle to cycle variation in work output can be the major cause of idle speed variations and so CoV_{IMEPg} has been used as a prime indicator of performance. Target values of CoV_{IMEPg} at idling speeds are typically around 3% under fully warm conditions [12-14]. Some degradation is to be expected at cold idle, but for acceptable idling quality, CoV_{IMEPg} is likely to be $<10\%$.

SPEED SWEEPS

A fixed main injection timing of 8°BTDC was used for pilot plus main strategies. Main quantity was varied with temperature as reported in Table 1 to achieve a target indicated work output approximately equal to FMEP for that temperature [15]. The pilot injection was $2\text{mm}^3/\text{str}$ in all cases. The end of pilot injection to start of main injection was kept constant at 10° to allow sufficient dwell between pilot and main for reliable main injection quantity. Engine speed was swept between 600 and 1400rpm at intervals of 200rpm for all temperatures. Values of CoV_{IMEPg} at all engine speeds are given in Figure 1.

Temperature [$^{\circ}\text{C}$]	Mq [mm^3/str]	Target IMEP _g [bar]
10	6	2
0	6	2
-10	8	3
-20	15	5

Table 1 – Nominal main fuel quantities for required indicated work output at each temperature

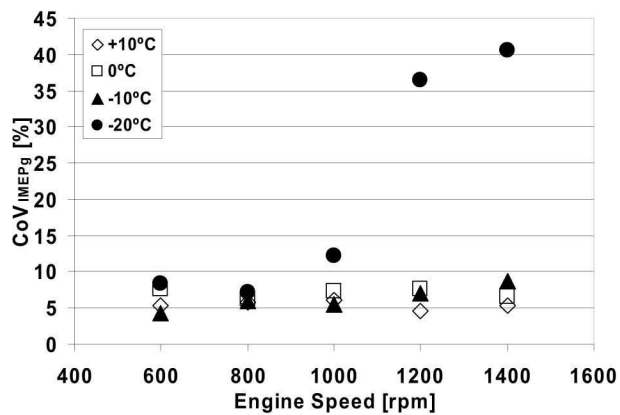


Figure 1 - Coefficient of variation of work output as a function of engine speed at four ambient temperatures, main injection timing 8°BTDC

At the three higher test temperatures CoV_{IMEPg} remained below 10% across the speed range. At $-20^{\circ}C$, however, there is a steep deterioration in stability as engine speed increases. To observe the sensitivity of these results to changes in injection timing, engine speed was fixed at a typical cold idle speed of 1000rpm and injection timings were varied between 16°BTDC and TDC. The results are given in Figure 2. Again there is a relatively low dependence on injection timing in this region apart from in the $-20^{\circ}C$ case and to a lesser extent at $-10^{\circ}C$.

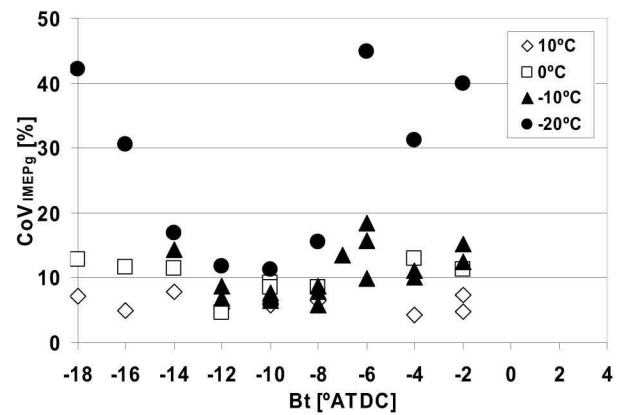


Figure 2 - Coefficient of variation of indicated work output as a function of main injection timing at four ambient temperatures, engine speed 1000rpm

In both cases the CoV_{IMEPg} quickly deviates from the desired $<10\%$ as injection timing varies from the optimum. An additional pilot injection was utilised to investigate any effect on stability at all temperatures. 2mm³/str was injected a nominal 10° in advance of the single pilot injection in the previous case and the main injection was reduced accordingly to keep total fuelling constant. The same technique was applied for all additional pilots. (Figure 15 on the final page is included to illustrate the relationship between the various injections.) Speed was kept at 1000rpm. The effect of the twin pilot strategy is shown in Figure 3.

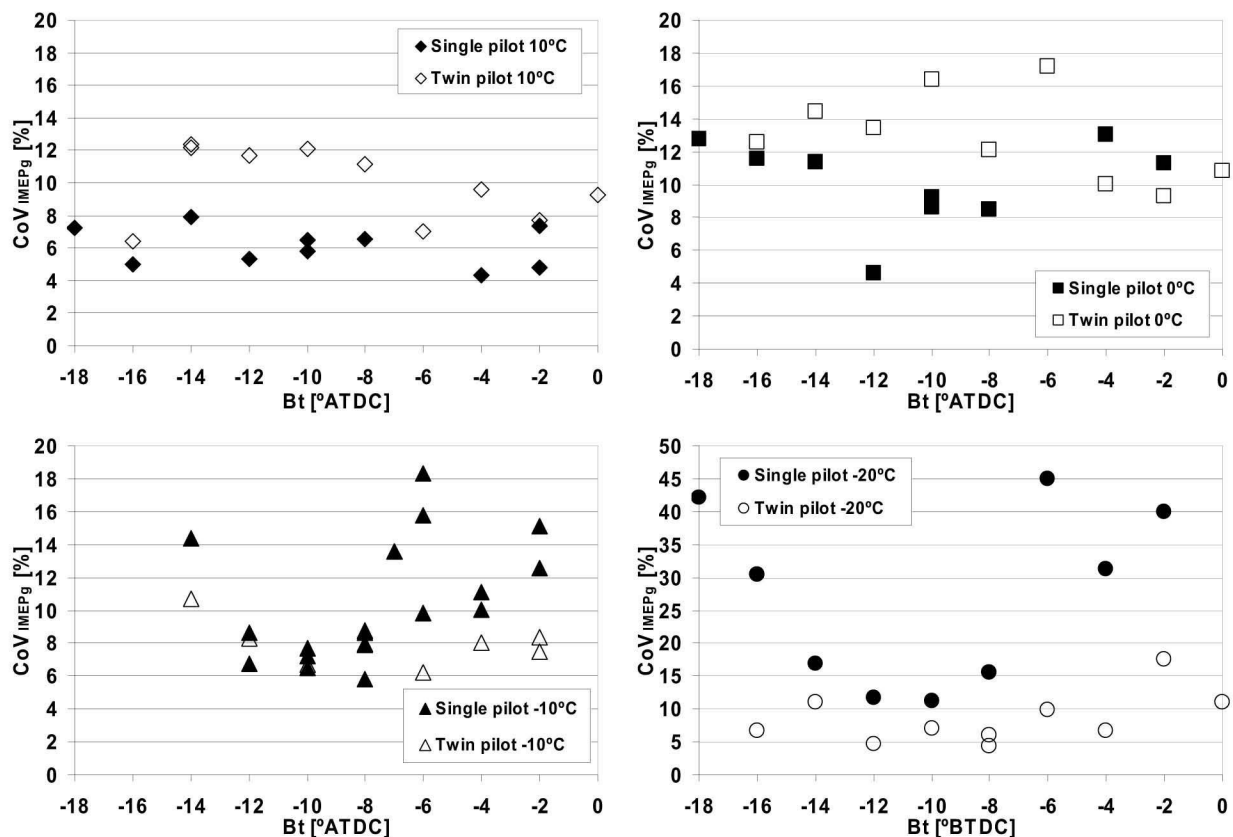


Figure 3 – Coefficient of Variation of indicated work output as a function of main injection timing at four temperatures utilising single and twin pilot strategies, engine speed 1000rpm

Although a single pilot is best at 10°C and 0°C , there are benefits to utilising a twin pilot at -10°C and at -20°C the twin pilot is clearly superior. At -10°C the $\text{CoV}_{\text{IMEPg}}$ is kept below 10% at all timings tested as opposed to 15% using single pilot. At -20°C the majority of test points return better than 10% $\text{CoV}_{\text{IMEPg}}$ with the worst at 20% compared to 45% for single pilot operation. Repeat points and a clearer trend showed that twin pilot operation also yielded more repeatable results, another indicator of stability.

The optimization of twin pilot quantities was examined in two stages, at the temperature where stability was worst, -20°C . First the total fuel quantity was held constant and the pilot quantities varied in increments of $2\text{mm}^3/\text{str}$ with various combinations of pilot up to a total quantity of $10\text{mm}^3/\text{str}$. Main injection timing was held constant at 8°BTDC and engine speed was 1000rpm . The IMEPg and $\text{CoV}_{\text{IMEPg}}$ results are given in Figure 4. (Note that the apparent, small, spread of results about each integer value of total pilot quantity has been introduced to show the symbols clearly and is not indicating a real variation in total pilot quantity.)

There is a clear improvement in average IMEPg and $\text{CoV}_{\text{IMEPg}}$ by utilising a twin pilot strategy – indicative of a reduction in poor cycles. As main quantity is reduced the IMEPg drops and we see the advantage of a small first pilot. It appears that the first pilot contributes to an increase in stability at the cost of work output. The best stability is achieved with a medium total pilot quantity, either 4,2 or 4,4. Any further increase in pilot quantity

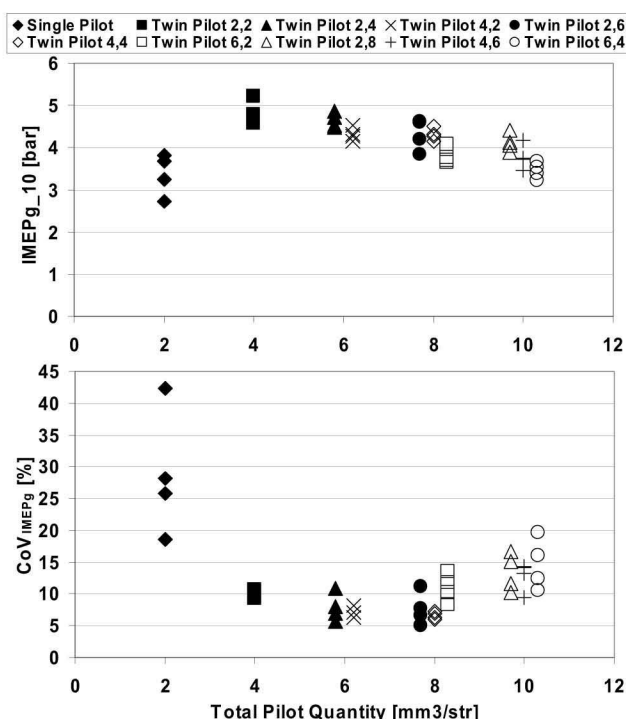


Figure 4 – Twin pilot optimisation varying pilot split and total pilot quantity, total quantity $17\text{mm}^3/\text{str}$, main injection 8°BTDC , -20°C , 1000rpm

sees a simultaneous reduction in IMEPg and cycle to cycle stability of IMEPg .

In the second stage of this optimisation the main quantity was held constant at $11\text{mm}^3/\text{str}$ as pilot quantity was varied, resulting in an increasing total fuel quantity. $11\text{mm}^3/\text{str}$ was used to maintain IMEPg at values around the desired 5bar target. The results for this investigation are plotted in Figure 5.

As expected there is an increase in IMEPg with increasing total fuel quantity and again the sacrificial role of the first pilot. Using a large first pilot reduces IMEPg to levels seen when using a lower total fuel quantity with no obvious improvement in stability. As IMEPg increases, the $\text{CoV}_{\text{IMEPg}}$ remains steady, which means the standard deviation increases in line with IMEPg . In pure stability terms then, the best solution is again a medium total pilot quantity which meets IMEPg demands at around 6-8% $\text{CoV}_{\text{IMEPg}}$.

It has been found that two pilots are more stable than one at -20°C , so the investigation was extended to consider three pilot operation. Again a $2\text{mm}^3/\text{str}$ pilot was added a further 10° in advance of the previous first pilot and the main quantity further reduced to $11\text{mm}^3/\text{str}$ from the $13\text{mm}^3/\text{str}$ used in the initial twin pilot sweeps. Engine speed was fixed at 1000rpm and the results for a sweep of main timings are given in Figure 6.

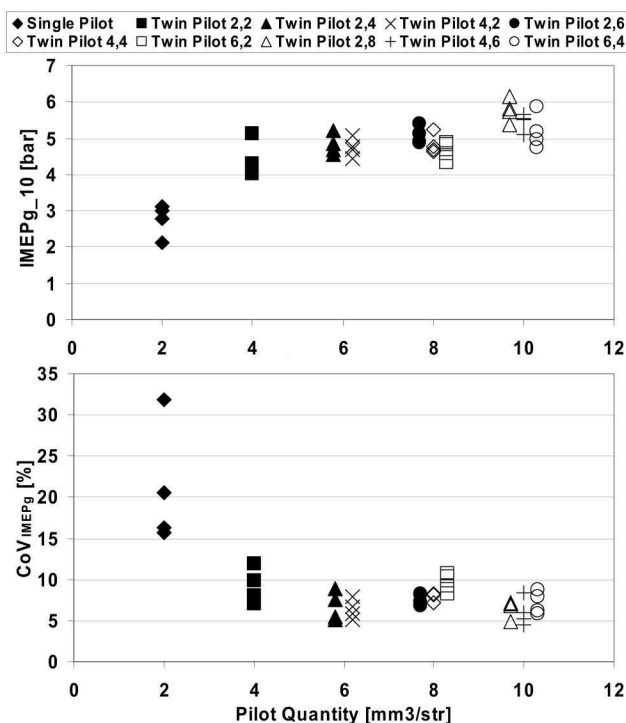


Figure 5 – Twin pilot optimisation varying pilot split and total pilot quantity, fixed main quantity $11\text{mm}^3/\text{str}$, main injection 8°BTDC , -20°C , 1000rpm