Characterizing Injection System Behaviour under Real Operating Conditions

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Abstract:

Injection systems have to be able to operate reliably and repeatably, under a variety of operating conditions. With today’s requirements for quieter and cleaner engines, multiple injection strategies have been introduced, giving one or two pilot injections, a main injection and one or two post injections. Any disturbance in parts of hydraulic systems, such as high pressure pipes, causes pressure waves to be set up in the pipes which, if they are not suitably damped, will affect the subsequent behaviour of the system. Thus a pilot injection, however small, will affect the injection rate and quantity of the main and post injections.

For engine development programmes, especially with high pressure common rail injection systems, it is important that the behaviour of the system and effect of one injection on subsequent injections is understood and can be measured.

In addition, the effects of environmental conditions, especially at temperatures well below 0°C for cold start, need to be documented, so that appropriate measures can be introduced to ensure that the engine can be repeatably and reliably started.

Introduction

The currently ever more stringent demands on internal combustion engines, whether for transportation or industrial applications, are placing greater demands upon injection systems and fuel injectors in particular. More precise control of injected quantity at extremely high pressures, smaller injection nozzle hole sizes, longer durability requirements with minimal deterioration and multiple injection strategies are taxing the injection system manufacturers’ development departments /1/. At the same time, the repeatable, reliable and accurate measurement of injection quantity and rate is becoming increasingly important, both for the development as well as control of the injector’s performance.

A typical passenger car diesel engine or heavy duty diesel engine at Euro 3 emissions levels could require up to three injections per combustion cycle /2/, while for today’s Euro 4 and Euro 5 engine strategies, four or more injections, ranging in size from 1-2mg/shot to more than 200mg/shot are being applied. An injector may inject two or more early or pilot injections, for noise or other reasons, before the main injection and then one or two post injections for control of soot emissions, followed by further injections to assist in the regeneration or operation of exhaust gas aftertreatment devices.

For the development or calibration engineer, one of the more difficult parts of the engineering process, is knowing exactly how much fuel has been injected into each of the shots. The majority of common rail injectors today, do not offer the possibility of using a needle lift injector. Neither is it possible to measure the quantity of fuel injected by each injection as the test bed fuel measuring system averages over many injections and cycles. Where only one injection per engine cycle takes place, the fuelling maps and measuring systems are normally adequate. However, when more than one injection per cycle occurs, size and shape of the second injection are influenced by the first injection.

As a typical example, Figure 1 shows the effect on emissions of nitrous oxides (NOx) and soot, as well as combustion noise and BSFC, of variations in the size of the second of two pilot injections for a 0.5l/cylinder passenger car diesel engine. The measurements were recorded at 1500r/min and 6 bar brake mean effective pressure. In addition, the cylinder pressures and rate of heat release for each of four consecutive cycles are shown in Figure 1. For the sake of clarity, the plots for each condition have been offset.

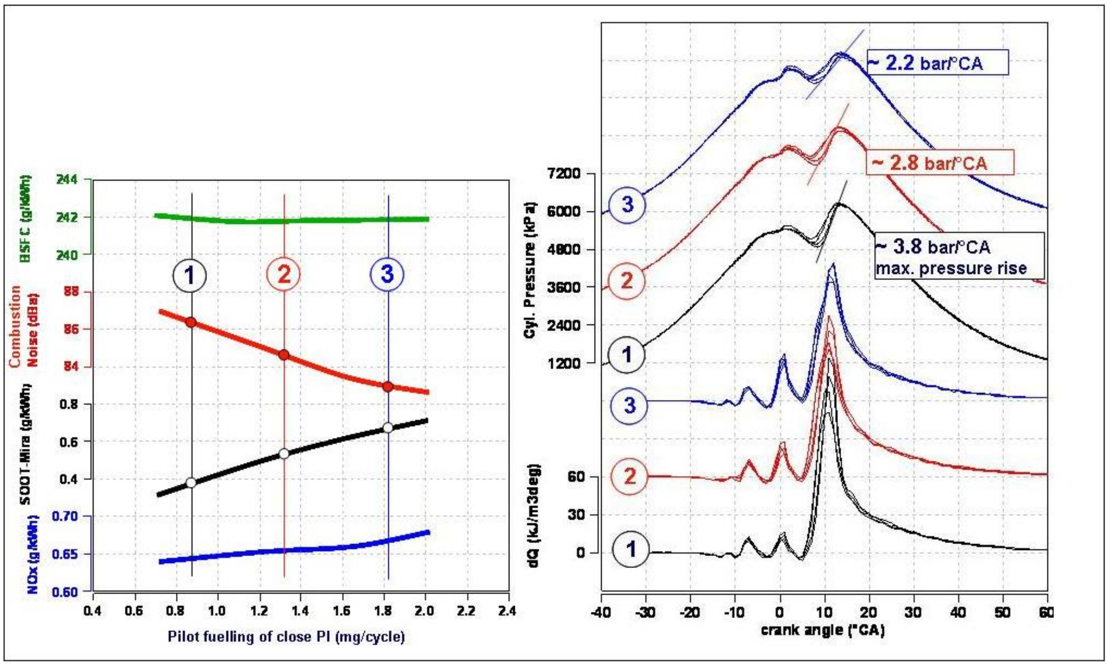


Figure 1- Effect of changes in close pilot injection quantity on emissions and performance

The fuel delivery of the second, or close, pilot injection has been increased by about 1mm^3 (from approximately 0.84mm^3 to 1.82mm^3) between points ① and ③. The effect of this increase can be seen in the cylinder pressure traces and rates of heat release. As the close pilot fuel quantity increases, the rate of cylinder pressure rise for the main combustion decreases from about 3.8 bar/° to 2.2bar/° and the peak rate of heat release reduces by about 15%. These changes are reflected in a reduction of combustion noise by 3.5dB(A), but at the cost of almost double soot emissions while the NOx emissions increase slightly.

In such cases, the total fuel delivery is measured on the engine test bed weighing system, but the actual fuel quantity injected may not equate with the values in the engine ECU. In order to determine the correct fuelling levels for each injection, the fuel system has to be measured on the injection test bench.

Multiple Injection Effects

As previously stated, any size of injection produces a pressure wave in the injection pipe which can affect any injection occurring afterwards. In order to demonstrate these effects, the pressure wave from a pilot injection and the injection rate shape is shown in the left hand diagram in Figure 2 together with the injection pulse to the injector and the motion of the measuring piston – which is proportional to the injected quantity. In this case the rail pressure has been set at 800 bar and the pump speed is 1000 rpm. The pilot injection duration is 260 µs, which corresponds to an injection quantity of about 2 mm³. The continuous black line shows the pressure wave caused by this injection.

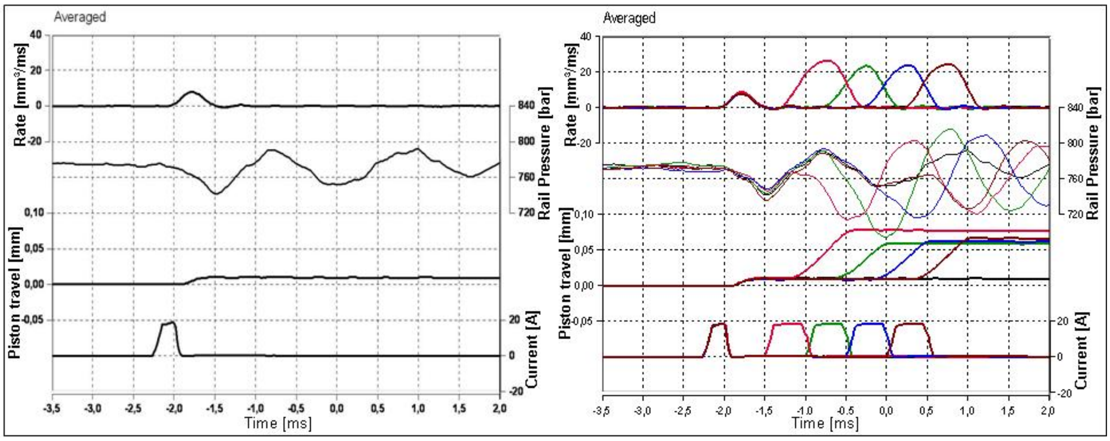


Figure 2 - Effect of Pilot Injection on Main Injections

Based on the basic calibration for this system, a main injection duration of 500 µs would normally correspond to an injection quantity of about 12 mm³. However, adding the main injection with a separation distance between the first and second injection drive pulses of about 760µs, gives a main injection quantity of 14mm³, although the pulse duration remains constant for both the pilot and the main injection. In this case, the separation is defined as the time between the start of the first and the start of the second injections. This can be seen from the red curve in the right hand diagram of Figure 2. Moving the separation between the main and pilot injections causes the main injection to start at different pressures and on rising or falling flanks of the wave generated by the pilot injection and results in variations in injection quantity as shown in Figure 3.

Thus the main injection shape and hence quantity, changes with the changes in the separation between the injections.

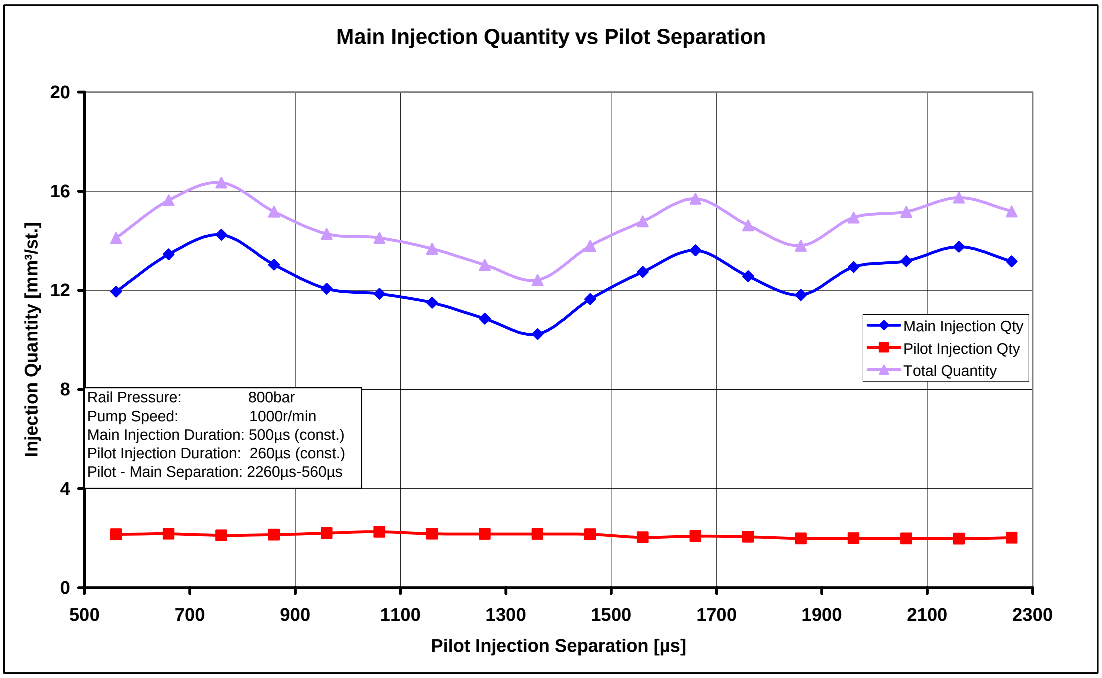


Figure 3 – Variation of Main Injection Quantity with Pilot Separation

Returning to the previous situation with two pilot injections, shown in Figure 1, the variations in injection quantity by moving the second pilot injection can be seen to be quite complex.

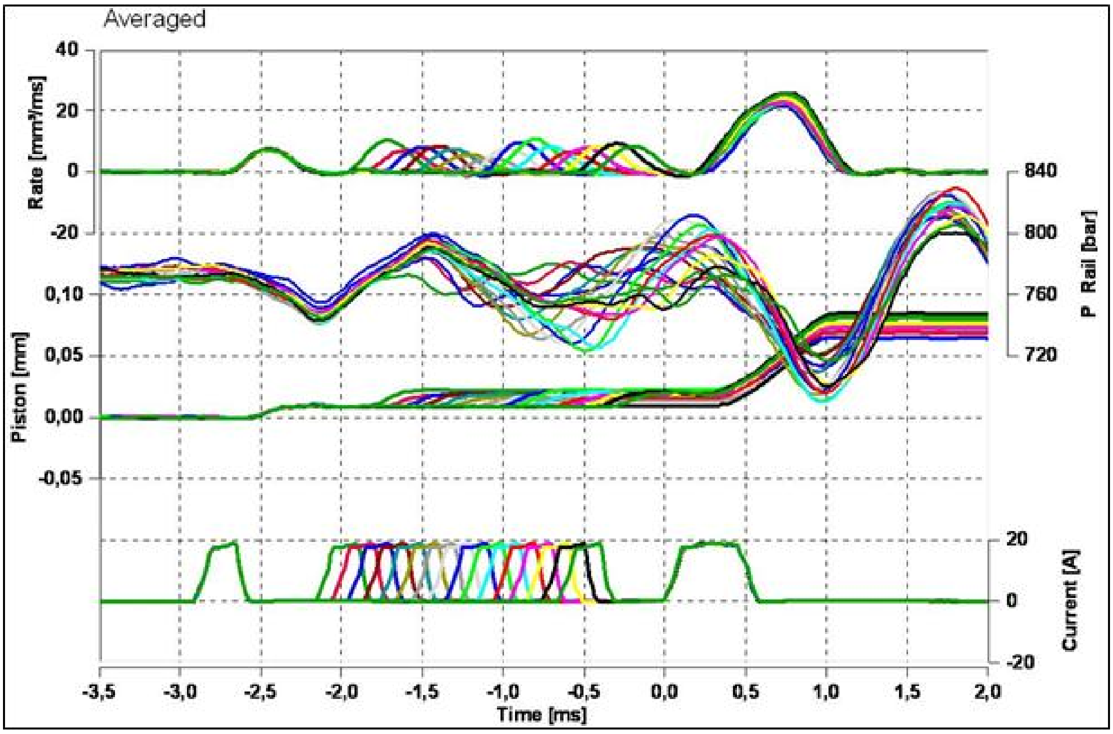


Figure 4 – Effect of Separation of Close Pilot on Main Injection

In this case the rail pressure was again held constant at 800 bar and the pump speed was 1000 rpm. Here both the first and second pilot injection durations were held constant at 260 µs, and the main injection duration was 500 µs. The first pilot injection and the main injection separation were kept constant and the timing of the second pilot injection was varied in 100 µs intervals. It is clear from the figure 4 that the change in separation between the second pilot injection and the main injection causes both injections to vary both in quantity and rate.

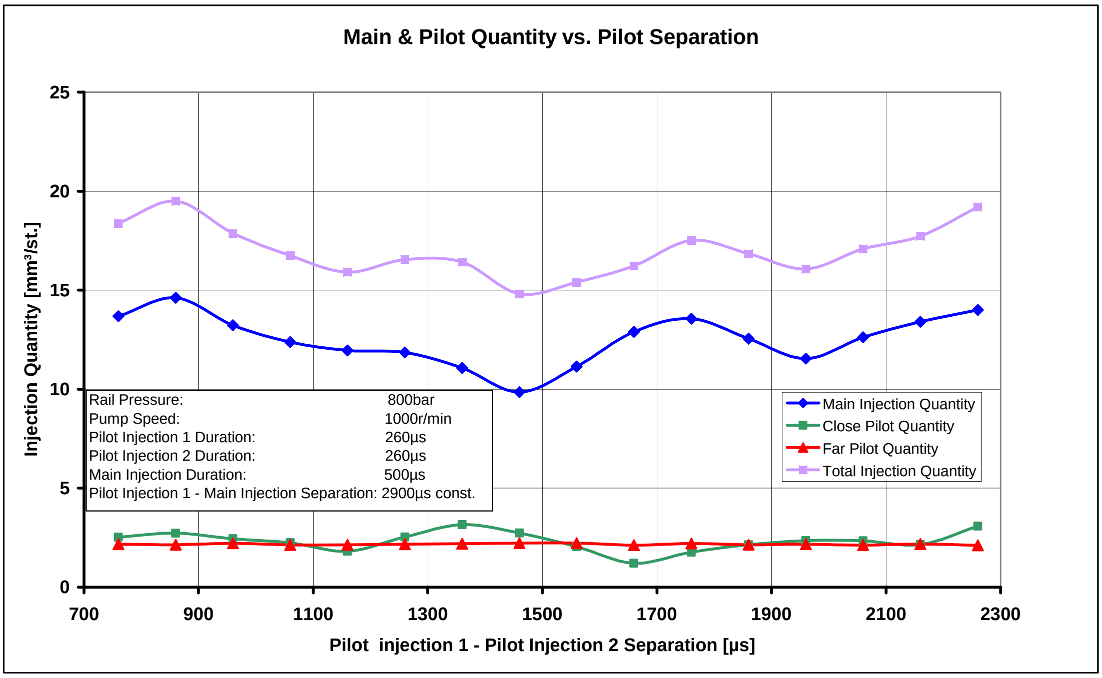


Figure 5 – Variation in Pilot 2 and Main Injection Quantity with Separation

The change in quantity of the injections is shown in figure 5. The second injection quantity, although it has the same duration as they first injection, varies in quantity between 3.2 and 1.4 cubic millimetres depending upon its timing, and the main injection quantity varies between 14.6 and 9.8 cubic millimetres. As a result the total injection quantity, which in theory should be no more than 16 cubic millimetres, varies between 19.6 and 14.9 cubic millimetres.

These effects are complex and cannot easily be compensated during calibration on the engine. Correction factors are available, but these must be calibrated for each injection system, as the wave effects are products of the physical geometry of the systems as well as the preceding injections.

For this reason, it is easier to pre-calibrate fuel injection system on the fuel injection test bench before applying the fuel system on the engine. By pre-calibrating the fuel injection system and the multiple injection system maps, the wave dynamics in the system can more easily be corrected.

Temperature Correction

In addition to the difficulties of calibrating the wave dynamic corrections for each individual injection, the calibration of injection quantities under different temperature conditions also presents challenges. At low fuel temperatures, the viscosity of the fuel is higher and can therefore affect the behaviour of the system. At high temperatures, the lower viscosity of the fuel increases leakage and restarting the engine can therefore be more difficult. Both at low and high temperatures, the presence of an injection pulse does not automatically mean that there is an injection.

For this reason, a fuel injection system hot and cold temperature test cell has been built. The cell has the following specification:

- Temperature Range: -30 to +140 °C (Components and Media)
- Control quality of fuel temperature 0.1°C in supply
- System setup based on flexible platform
- High pressure pump drive power: max. 45 kW, max. 6000 rpm
- Fuels: Test oil to ISO 3114, Exxsol D40, Diesel, Gasoline, DME
- 6 Cylinder instrumented with *AVL Shot to Shot* measurement system
- Optimization and Calibration of complex Functions using CAMEO/IndiCom

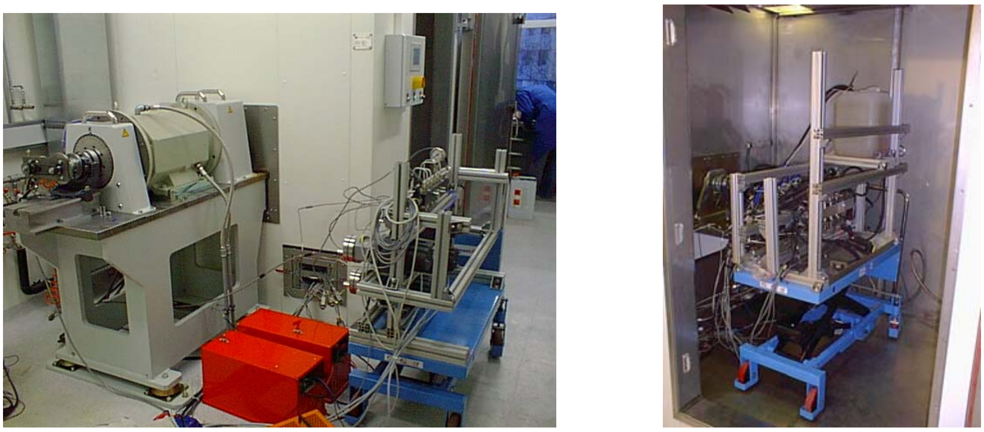


Figure 6 – Fuel System Temperature Test Cell showing Motor and Fuel System inside Cell

The test cell allows the fuel system to be tested either outside or inside the temperature chamber as the motor has been arranged to allow access to both ends of the drive shaft, one end of which is inside the test cell. The fuel system can then be installed either inside or outside the cell for measurement. Measurements of fuel injection quantity are made using the AVL STS PLU system.

With this cell fuel injection systems can be tested and pre-calibrated before their engines are put in the cold chamber and much of the uncertainty as to the presence and size of the injections can be removed.

As an example of the effect of different temperatures on fuel systems, a common rail system was fitted to the test cell. Measurements were made of the injection pulse duration and injection quantity at room temperature (+25°C) for fuel quantities of about 2mg, 5mg, 10mg and 15mg/injection at an equivalent engine speed of 200r/min and 250 bar rail pressure. The cell was cooled to -5°C, -15°C and -25°C and the measurements repeated with the same settings for rail pressure and injection pulse duration. The results are shown in Figure 7.

Whereas the rail pressure remains fairly constant with temperature, there are large variations in injection quantity for the given pulse durations.

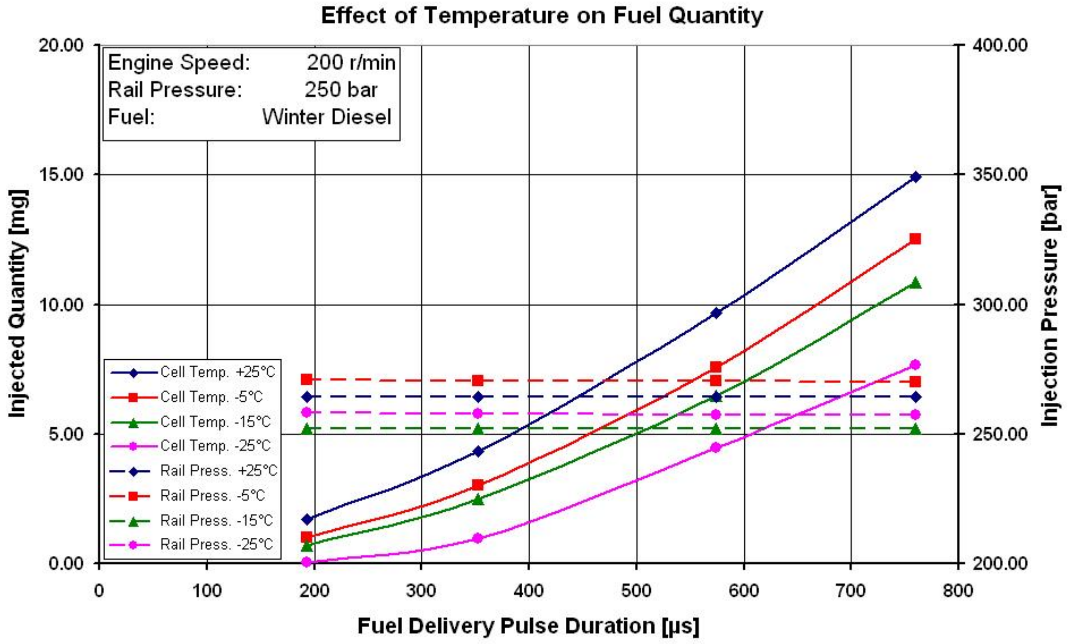


Figure 7 – Effect of Temperature on Fuel System Behaviour

It can seen, that the injected fuel quantity reduces with temperature and for an injection pulse duration of 195µs, which gave an injection quantity of 2mg/injection at +25°C, no injection could be measured at -25°C. The injection quantity of 15mg under normal temperatures, was reduced by around 50% at -25°C. Even at -5°C, there was a noticeable drop in injected quantity (~15%), which could in turn lead to increased difficulties in engine starting.

When doing cold start testing, it is normal to record the injection pulses, injection pressure and cylinder pressure while monitoring the cold start. However, from the above measurements, the presence of the injection signal and rail pressure does not mean that there as an injection at low temperatures.

By investigating the effects of temperature on both the pilot and main injections at cold start, an effective strategy can be developed in advance of engine testing, which can save extra engine testing in the cold chamber.

Test Bench Description

In order to make accurate measurements of multiple injections, a precise and repeatable measuring system is necessary. The system must have the ability to differentiate between individual injections and record many injections for later analysis.

The injection and measurement system set up for a typical common rail system is shown in Figure 8. The high pressure fuel pump is driven by an electric motor and each injector feeds directly into a separate measuring device, in this case AVL PLU STS measuring devices. The injectors can either feed directly into the devices (preferred method), or they can feed into Bosch acoustic tubes which are attached to the measuring devices.

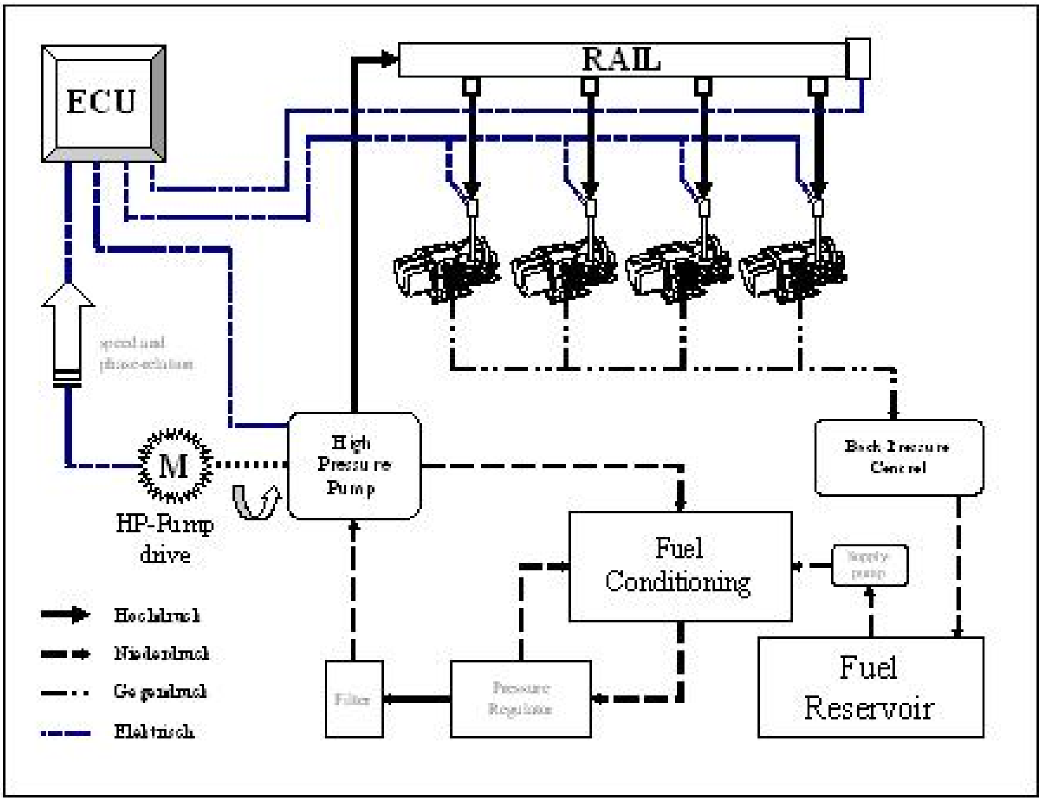


Fig. 8 - Test Set Up

In order to make the measuring conditions as realistic as possible, the back pressure applied to the injection nozzle is controlled as a function of the corresponding engine load.

The PLU STS Measuring System

The heart of the test benches is the AVL Pierburg STS measuring device and is based on the well established PLU flow sensor and is shown in Figure 9.

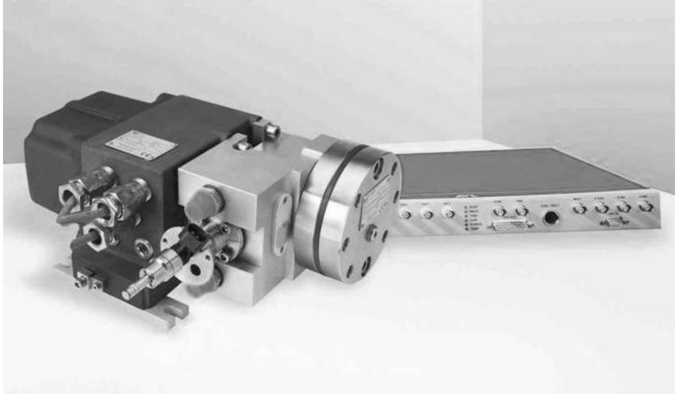


Figure 9 - PLU 131 HP STS flow sensor

The PLU flow sensor is a volumetric measurement principle. It combines in parallel a rotational and a translational flow sensor principle, Figure 10, in one single system /3/.

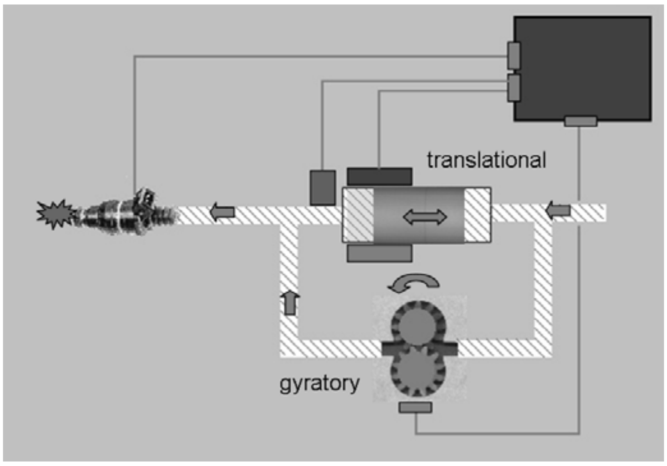


Figure 10 - PLU flow measurement principle

The rotational (or gyratory) principle is a servo driven high precision gear head counter incorporating the high precision base calibration of the flow sensor. The translational principle works as a high speed physical flow integrator and is also responsible for the zero pressure-difference over the instrument. The zero pressure-difference principle allows the instrument to avoid any interaction with the system analyzed while being able to sense time resolved flow. Other features originating from the zero pressure difference principle are the wear free operation of the gyratory flow sensor, its life time calibration and its invariability against viscosity effects.

To cope with the density of the fuel, Figure 10, the translational flow sensor is adjusted to the density of the fluid of approx. 0,75 g/cm³.

This system provides both:

- excellent flow rate curves in combination with
- lowest measurement uncertainties for single and multiple shot quantities.

Measurement Uncertainty Budget

In order to guarantee accurate measurement of individual shot quantities, not only does one needs an excellent measuring device, but the complete test set up, Figure 8, has to be designed and approved accordingly.

Based on the functional requirements, the measurement process was characterized in detail, in order to achieve *precise and correct* measurement results as defined below.

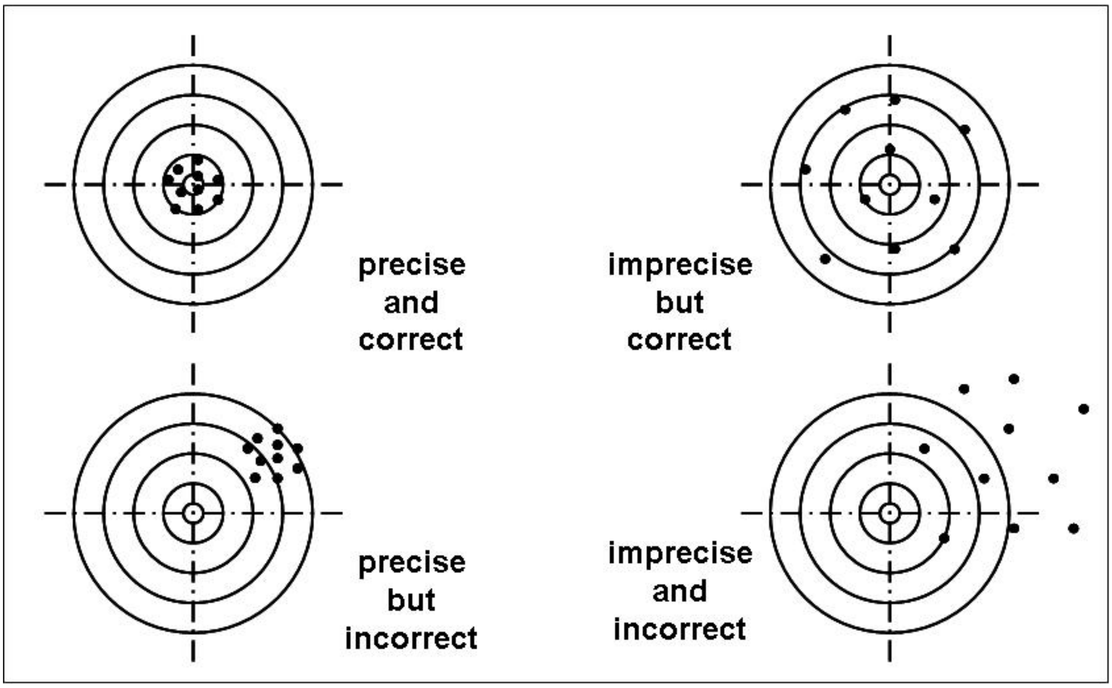


Figure 11 - Target – Analogy according to ISO 3534-1

The Guide to the expression of Uncertainty in Measurements (GUM) /4/ has become internationally accepted since 1995 as the body of legislation for the evaluation of process orientated combined measurement uncertainties

As the basis for the determination of combined measurement uncertainties according to GUM, a clear definition of influencing variables, the so called measurement uncertainty-budget, for the measurement results are required, helping to define the performance of the complete test set up, Figure 11.

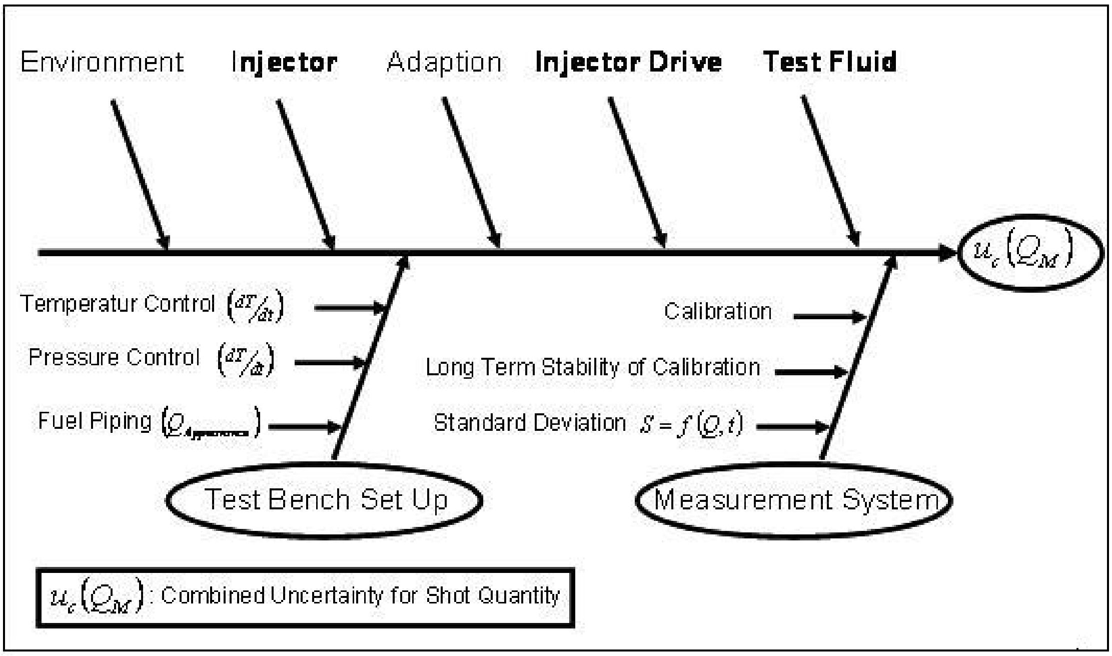


Figure 12 - Fish Bone Diagram “Causes for Measurement Uncertainty”

Figure 12 shows that a perfect measurement device can not guarantee perfect measurement results by itself. Minimized combined measurement uncertainty can be achieved by optimizing the combinations between all the components involved in the measurement process.

Discussion of Achieved Measurement Results

It would go beyond the scope of this paper to provide from a complete and detailed measurement uncertainty budget the combined measurement uncertainty for achievable results according to GUM.

However it is possible to determine combined uncertainties for achieved measurements under the assumption, that the non-systematical influence of all relevant standard uncertainties are within the standard deviations for the average values indicated by the measurement unit.

For the combined measurement uncertainty of indicated average values, the following relationship applies:

$$u_c(Q_M) = \sqrt{u_Z^2(Q_M) + u_L^2(Q_M) + u_T^2(Q_M) + u_K^2(Q_M)}$$

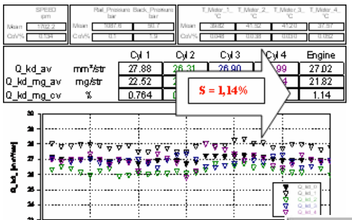
Q_M Shot Volume

$u_c(Q_M)$	Combined Uncertainty of Q_M
$u_Z(Q_M)$	Standard Uncertainty for measuring time (cycle time) under operational conditions
$u_L(Q_M)$	Standard Uncertainty for long term calibration stability
$u_T(Q_M)$	Standard Uncertainty for temperature influence
$u_K(Q_M)$	Standard Uncertainty for calibration under laboratory condition

The dominating element in this is the Standard Uncertainty for the cycle time under real operational conditions. This uncertainty includes the non systematical influences of the measuring system, the test set up respectively its temperature and pressure control, the injector itself, its driver and the test fluid.

All other influences are additionally relevant for the measuring system.

As an example the Combined Measurement Uncertainty for a measurement at 1700rpm engine speed and a shot quantity of 27,02mm³/cycle is determined as follows:



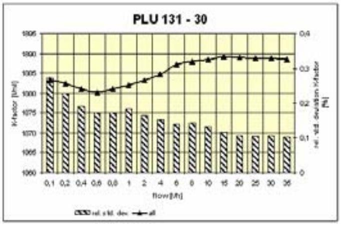
SPEED rpm	Mean	1702.2
	CoV%	0.134

	Rail_Pressure bar	Back_Pressure bar
Mean	1087.6	50.7
CoV%	0.1	1.9

	T_Motor_1_ °C	T_Motor_2_ °C	T_Motor_3_ °C	T_Motor_4_ °C
Mean	39.82	41.52	41.20	37.57
CoV%	0.048	0.038	0.030	0.052

		Cyl 1	Cyl 2	Cyl 3	Cyl 4	Engine
Q_kd_av	mm³/str	27.88	26.31	26.90	[illegible]	27.02
Q_kd_mg_av	mg/str	22.52	[illegible]	[illegible]	[illegible]	21.82
Q_kd_mg_cv	%	0.764	[illegible]	[illegible]	[illegible]	1.14

$$u_z(Q_M) = \frac{1{,}14\%}{\sqrt{30}} = 0{,}208\%$$

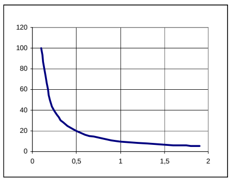


Distribution: Normal
s= 0,15 %

$$u_L(Q_M) = \frac{0{,}15\%}{\sqrt{12}} = 0{,}043\%$$

$$Q_{false} = \frac{dT}{dt} \times \beta \times V_{Meas}$$

$$B_{Temp} = \frac{Q_{false}}{(Q,m)_M} = \frac{dT}{dt} \times \beta \times \frac{V_{Meas}}{(Q,m)_M} = 0{,}2\%$$



$$u_T(Q_M) = \frac{0{,}2\%}{\sqrt{24}} = 0{,}041\%$$

Braunschweig, den 24.02.88
Im Auftrag

Dr.-Ing. Ka
Oberregierun

$$u_k(Q_M) = \sqrt{0{,}04^2 + 0{,}16^2} = 0{,}041\%$$

$$u_c(Q_M) = \sqrt{0{,}208^2 + 0{,}043^2 + 0{,}041^2 + 0{,}041^2} = 0{,}211\%$$

Coverage factor k=2 (95%)

Total Combined Measurement Uncertainty including influence of test rig and injector:

$$\pm u_c(Q_M) = 0{,}422\%$$

Summary

For the characterisation and calibration of fuel injection systems with multiple injections, it is important to assess the behaviour of the complete system on a shot to shot basis before attempting to calibrate the system on the engine. The enables the influence of one injection on the next to be documented and compensated for in advance, thus saving time and effort on the engine.

In addition, the effects of temperature on the system should also be assessed and suitable strategies implemented before cold start engine testing begins, thus enabling more rapid calibration and efficient use of the cold test dells.

Because of these factors, it has been found to be advantageous to build specific fuel injection system test facilities to enable:

- shot to shot and injector to injector differences to be determined early in the test programmes,
- the effects of different ambient conditions on fuel injection system behaviour to be assessed in advance of climatic testing

Due to its accuracy, repeatability and ability to measure a large number of individual injections per engine cycle, the AVL PLU 131 STS is an ideal tool to use as a basis for such facilities.

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