A Benchmark Study on the Flow Metering Systems for the Characterisation of Fuel Injectors for Future Heavy Duty Commercial Vehicles.

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Abstract

This study aims to determine the most suitable flow metering device for the characterisation of heavy duty diesel injector behaviour. The study focuses on three commercially available metering devices and the main principles they employ. An experiment was carried out to benchmark the performance of each device's measurement repeatability in the characterisation of fuel injector behaviour. This study then compares the capabilities and suitability of each for use in a production environment. The comparison was carried out for Delphi Technologies using the new DFi21 heavy duty diesel injector which uses the miniaturised hydraulic three way control valve technology [1].

Introduction

Heavy duty engine manufacturers are continuing to improve fuel efficiency and reduce emission levels through the design and manufacture of improved fuel systems. The emission regulations introduced over the past decade have meant engine manufacturers have required improvement in fuel delivery accuracy and in the capabilities fuel injection systems. These capabilities allow for more complex combustion strategies, higher injection pressures and higher nozzle flow rates. In addition more recent challenges from alternative powertrain solutions, such as hybrid or full electrification, have intensified the demand for improved fuel economy in commercial vehicles [2]. To enable the efficient production of these fuel systems, specifically the fuel injector elements, testing and behaviour characterisation are required to ensure product requirements are met. The calibration of injector behaviour has a measurable effect on overall engine performance [3] and this can depend on a manufacturer's ability to measure the fuel delivery during the final production test. An injector's ability to repeat multiple consistent fuel deliveries within a fraction of a second and to maintain this performance across months or years, are also key requirements for metering systems. Shot to shot and test to test are two criteria the performance of a metering system can be measured against. The requirements for this next generation of heavy duty diesel engines, and notably the increase in injection pressures to three thousand bar, increase the rate of energy being input into a metering device, pushing existing metering systems to the limits of previously explored measurement reliability and hardware capabilities. Engine manufacturers have avoided the need for high injection pressures through the heavy use of Selective Catalytic Reduction (SCR) in exhaust systems. However the focus of new regulations on the further reduction of nitrogen oxides emissions and the continued costs of exhaust treatment systems are pushing manufacturers towards Exhaust Gas Recirculation (EGR) alternatives [4].

Flow Metering Device Measurement Methodologies

The three main devices this study focused on were a nitrogen backed piston displacement device, a chamber pressure constant drain device and a rate tube. Each device is a commercially available device which rely on well-established but varying measurement methodologies. This paper is not an exhaustive study of fuel injection metering systems, additional systems exist which are viable for use in production testing [5,6,7] while some methods are exclusively suitable for laboratory study [8].

The Nitrogen Backed Piston Displacement Device

Devices that use the method of piston displacement infer the mass of the fuel delivered from the movement of a piston. They are in extensive use throughout the industry [9], particularly within the heavy duty diesel industry due to their ability to accurately meter high pressure injections.

The measurement principle relies on the system's ability to detect the movement of a low mass piston using a linear displacement sensor and a temperature sensor monitoring the conditions within the measurement chamber. The fuel injection is directed into a chamber causing the piston to move due to the extra volume. The piston is backed by inert gas pressure to ensure the piston stays in contact with the fluid. The hydraulic layout of the device is shown in Figure 1. Its movement, along with the temperature within the chamber can be used to calculate the mass of fuel and the rate of injection into the chamber. Before the next measurement cycle a valve connected to the chamber opens to return the system to a starting state. The injected mass is estimated using Equation 1.

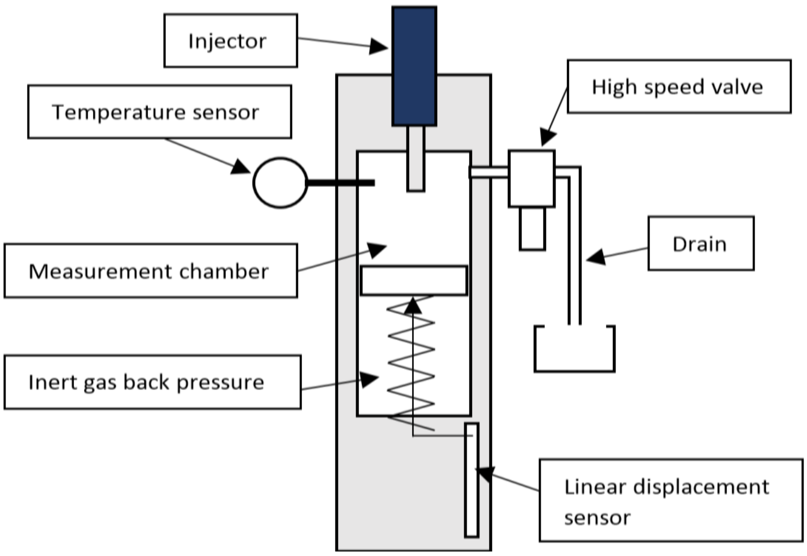

Figure 1 - a diagram representing a piston displacement device [10].

$$\mathrm{m} = \rho \,.\, (P_{start} - P_{end}) \,.\, A$$

Equation 1 - Fuel mass equation governing the piston displacement measurement principle. Where *m* is the mass, ρ is fluid density, P_{start} & P_{end} are the start and end positions of the piston. *A* is the cross sectional area of the piston face.

Piston displacement devices are moderately complex mechanical devices and can be difficult to maintain. They are an inviting solution for use in the development and production of fuel injectors due to the robust fuel mass measurement as the device relies on a volume measurement which is far less susceptible to dynamic effects than a pressure measurement device. It is also robust against changing conditions within the device due to the temperature sensor managing the changes in fuel density and bulk modulus [10]. The high speed actuation valve used to drain the chamber between injections allows for a high measurement frequency resulting in low production cycle times.

Both the potential pressure and injection flow rate requirements for the next generation of injectors are pushing the capabilities of the current designs due to the maximum fuel mass the units are able to accept per cycle. The new requirements of Euro 7 testing exposed the limitation of the device examined in this study and exposed flaws in the piston displacement method specifically during multiple injection type characterisation. The injection rate is the derivative of the piston displacement and at higher pressure and flow rates can exhibit noise at the end of injection, visible in the rate measurement [9]. While this does not prevent the calculation of the total mass delivery, it does degrade the device’s ability to characterise the injection rate and the capture of small hydraulic events shortly after high energy inputs into the system. Furthermore, the performance of the device can be heavily dependent on the chamber drain valve which has to be precisely tuned after each regularly required maintenance cycle, requiring skilled support throughout the devices use.

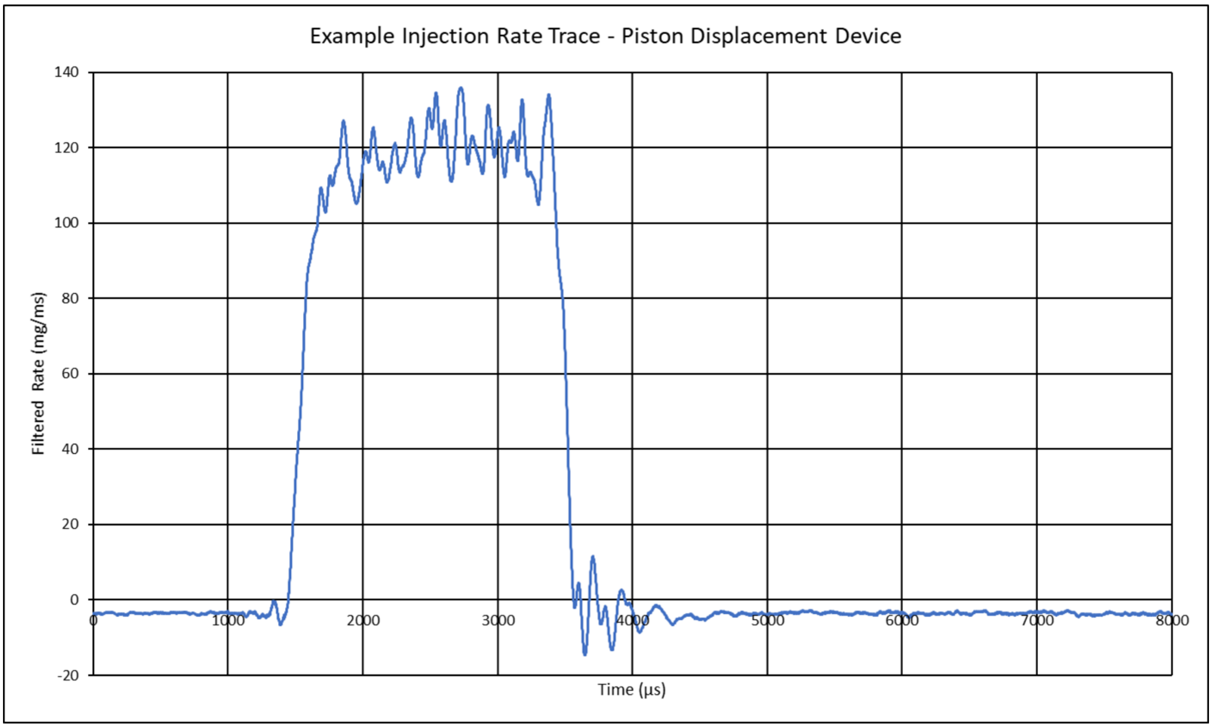

Figure 2 - Injection rate trace produced by a piston displacement device showing the “ringing” effect at the end of injection.

The Chamber Pressure Constant Drain Device

A constant drain chamber device uses the pressure rise seen within a chamber to calculate the mass of fuel injected. These devices have been through several iterations [9][11] and are used extensively in the light and medium duty industries for both liquid and gas flow metering. In recent years this device has been developed for the high flows and pressure requirements of the heavy duty commercial vehicle and for high volume production applications; chamber design to reduce pressure wave activity and a drain valve capable of regulating the chamber pressure across a range of injection quantities.

The conditions within the chamber are monitored using a pressure transducer and a temperature sensor mounted in the chamber wall. During periods when there is no injection into the chamber the pressure decays due to the drain valve. This drain rate is dictated by the position of a needle within the valve which is set by an electronically controlled stepper motor acting to maintain a stable chamber pressure. During injection the chamber is still draining at a constant rate but the deviation from the expected pressure can be used to calculate the fuel mass delivered into the chamber. To compensate for the changes in fuel density and the bulk modulus within the pressurised chamber, a Coriolis meter is used to monitor the drain flow rate which can be validated using the thermocouple monitoring the chamber interior. The hydraulic layout of the device is shown in Figure 3.

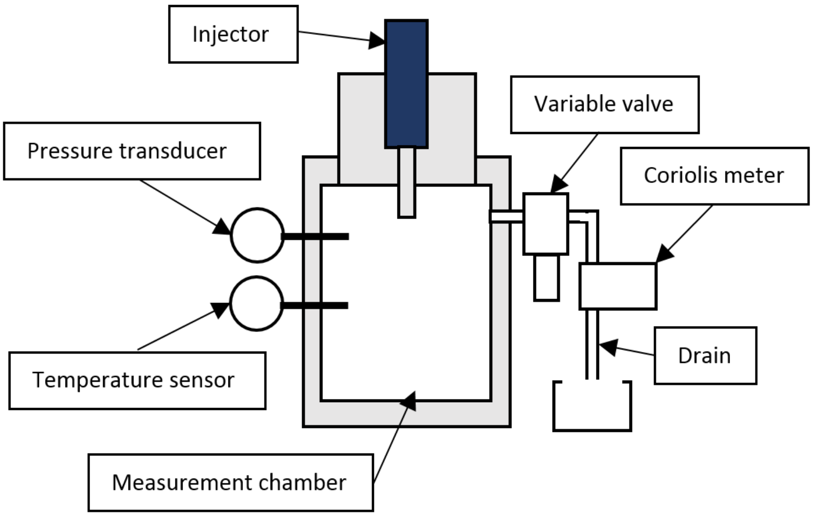

Figure 3 - a diagram representing a chamber pressure constant drain device.

$$K = V . \frac{dP}{dv} \qquad (2)$$

Equation 2 - The bulk modulus of a fluid is a function of the pressure and temperature which determines the compressibility of a fluid [12]. Where *K* is the bulk modulus of the fluid, *V* is the chamber volume and *P* the chamber pressure. The bulk modulus is important in determining the mass of a fluid under pressure.

$$\frac{dm}{dt} = \rho \cdot \frac{V}{K} \cdot \frac{dP}{dt} \qquad (3)$$

Equation 3 - Fuel mass equation governing the chamber pressure measurement principle for a closed chamber [12]. Where m is the mass of fluid and ρ is the density of the fluid. A constant drain device must compensated for the flow out of the chamber during injection.

Constant drain chamber devices are mechanically simple with few moving components. relying pressure rise instead to infer the fuel mass delivery from a dynamic pressure trace. They are easy to maintain making them another inviting solution for production. The principle of chamber pressure device with a constant drain requires that the flow out of the chamber is accounted for. This is done by modelling the discharge from the drain valve for a given pressure over a period of time. During an injection, and with the pressure within the chamber rising, this discharge rate can be accounted for.

Chamber pressure devices normally require a significant amount of set up time for each application to ensure the drain process is correctly set to minimise the risk of an over pressurisation of the measurement chamber which can damage the device. The method used for chamber drain varies across devices [9]. A constant drain device reduces the set up time by utilising an electronically controlled drain which can adjust the drain rate to maintain a stable back pressure. The computer control of the chamber pressure allows the system some degree of flexibility when subjected to different applications, however extra set up work is required to optimise the measurement frequency a device of this type can achieve. For a production application an increase in measurement frequency can lead to a valuable reduction of cycle time. The device can therefore allow for high measurement frequencies but is still limited by the maximum flow rate of the drain valve.

This chamber pressure device can derive the injection rate by taking the derivative of the chamber pressure, however this signal does require significant signal filtering to smooth high frequency resonances within the chamber. The injection of a large fuel quantity into a relatively small chamber leads to the resonance of the chamber walls causing high frequency pressure wave reflections to appear on the pressure sensor signal. This noise must be removed using signal filtering before subjecting it to analysis. Low pass filtering can lead to the distortion of the observed injection rate and shifts the start and end of injection [13]. The injection rate produced by this chamber pressure device does not suffer artefacts like the other two devices but due to the heavy signal filter does lose some detail. Still the lack of an artefact at the end of injection allows for the characterisation of close coupled injections. As with other chamber devices the maximum drain rate of the needle valve leads to a trade-off between injection frequency and injection flow rate. For application outside of the design envelope this could lead to increased cycle times in production testing applications. The compensation for fuel density and the bulk modulus within the chamber is measured using a Coriolis meter which captures fuel from the drain valve, requiring a period of stable injection quantity into the system before a measurement is taken.

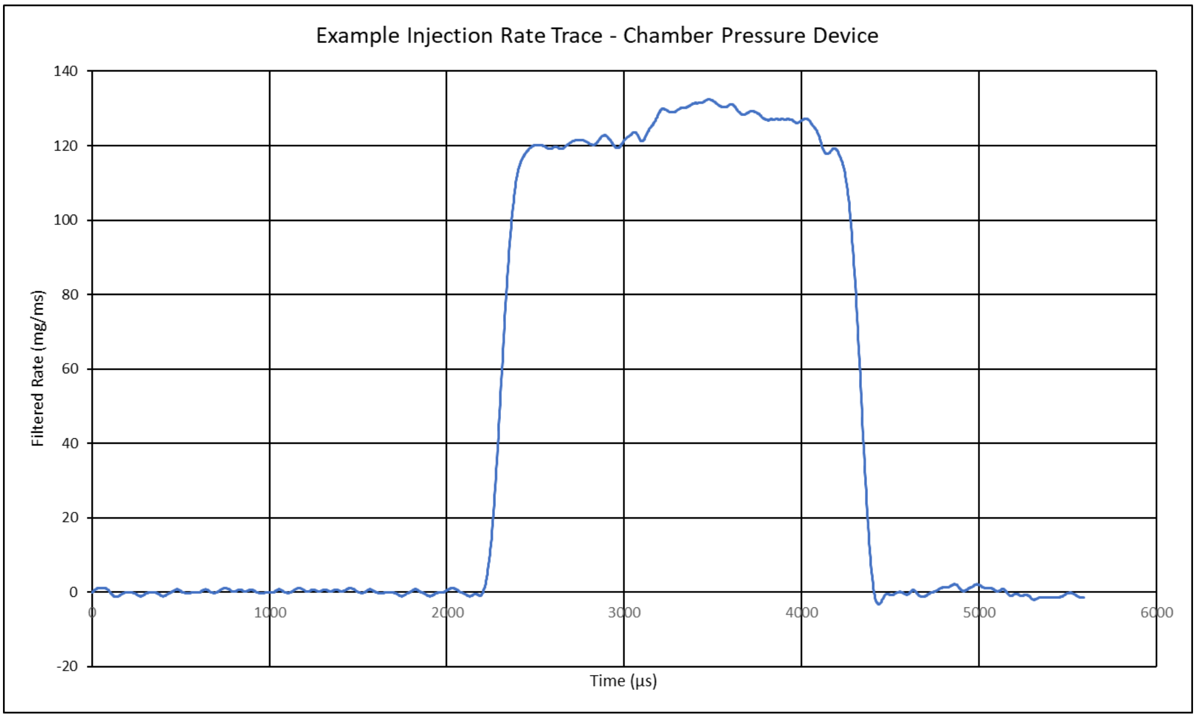

Figure 4 - Injection rate trace produced by a chamber pressure device. Note the heavy filtering applied to the signal.

However this potentially lost time in each cycle could be avoided by using the temperature sensor mounted in the chamber for the density and bulk modulus calculations. The assumption of fluid characteristics through temperature is used on other flow meter devices but requires the correct compensation algorithms which must, in this case, accurately model the behaviour of a relatively large volume of fluid with a single point of observation.

The Rate Tube Device

Rate tube devices have been used since the 1960s and have been through many different iterations which have led to incremental improvements in hardware and software to overcome some of the limitations of the rate tube method [14]. One such improvement has been the characterisation of a thermally driven signal float which disrupts the capture of the end of injection [4,15]. The device used in this study consists of a measurement tube with a pressure and a temperature sensor mounted at the end where the injection is captured. An orifice and a pressure regulator are used to manage the drain of the device and to maintain back pressure within the tube. Figure 5 represents the basic hydraulic layout of a rate tube. During an injection the local pressure around the nozzle tip increases and propagates along the fluid column within the tube. This increase in pressure and subsequent drop in pressure once the injection has stopped, is directly proportional to the injection rate [10]. The pressure wave travels unimpeded up the tube until it reaches a restriction and is then reflected back along the tube once again acting upon the pressure sensor. This reflection can travel back and forth along the tube several times before the system reaches a state of quiescence. The length of the tube, and therefore the time required for the reflection to travel back and forth along the tube, determines the maximum duration of injection the device can capture [14]. This pressure trace is then integrated to give the volume of fluid injected. A temperature compensation algorithm then allows this volume to be calculated into mass.

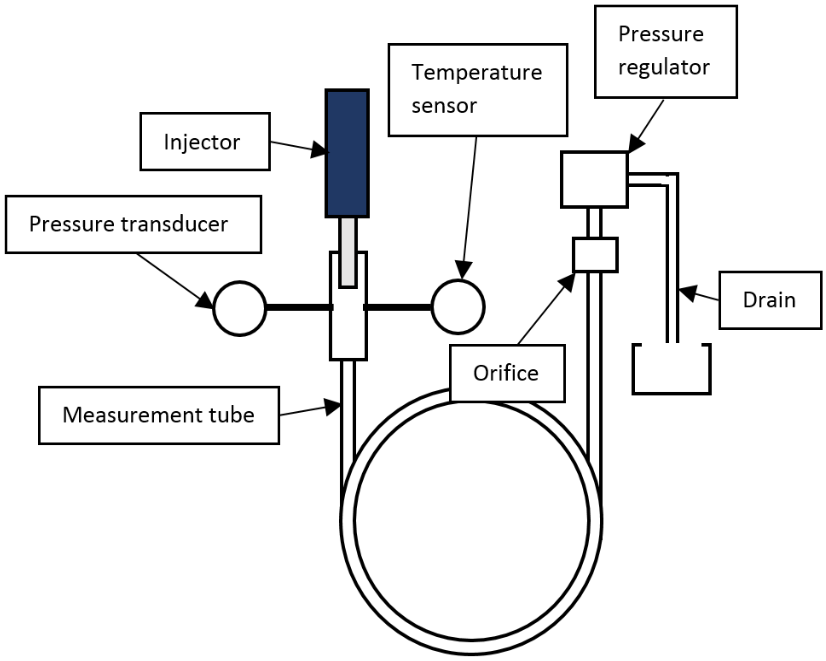

Figure 5 - a diagram representing a rate tube [13].

$$\mathrm{m(t)} = \frac{A_t \, . \, \Delta p(t)}{a} \quad (4)$$

Equation 4 - Fuel mass equation governing the rate tube measurement method [12,17]. Where $\mathrm{m(t)}$ is the fuel mass flow rate, A_t is the cross sectional area of the tube, $\Delta p(t)$ is the pressure increase over the hydraulic volume of the device and a is the speed of sound in the fluid medium within the device.

Rate tube devices are very flexible, and require very little setup time for each application. The fuel mass calculation is relatively simple as the injection rate is directly proportional to the pressure within the tube. The iteration of rate tube device used in this study had a number of adaptations to improve its measurement performance at high injection pressures and reduced cycle time. The device uses an inert gas to backpressure the measurement tube which has the effect of reducing fluid cavitation and the noise this produces on the pressure signal [18].

The selection of chamber geometry design can also been used to reduce and mitigate signal noise due to resonance and acoustic artefacts within the device [16]. The device can also utilise software algorithms to reduce the effect of rate distortion due to temperature and friction within the tube [15] reducing the amount of time that is required for the temperature in the device to stabilize before measurement.

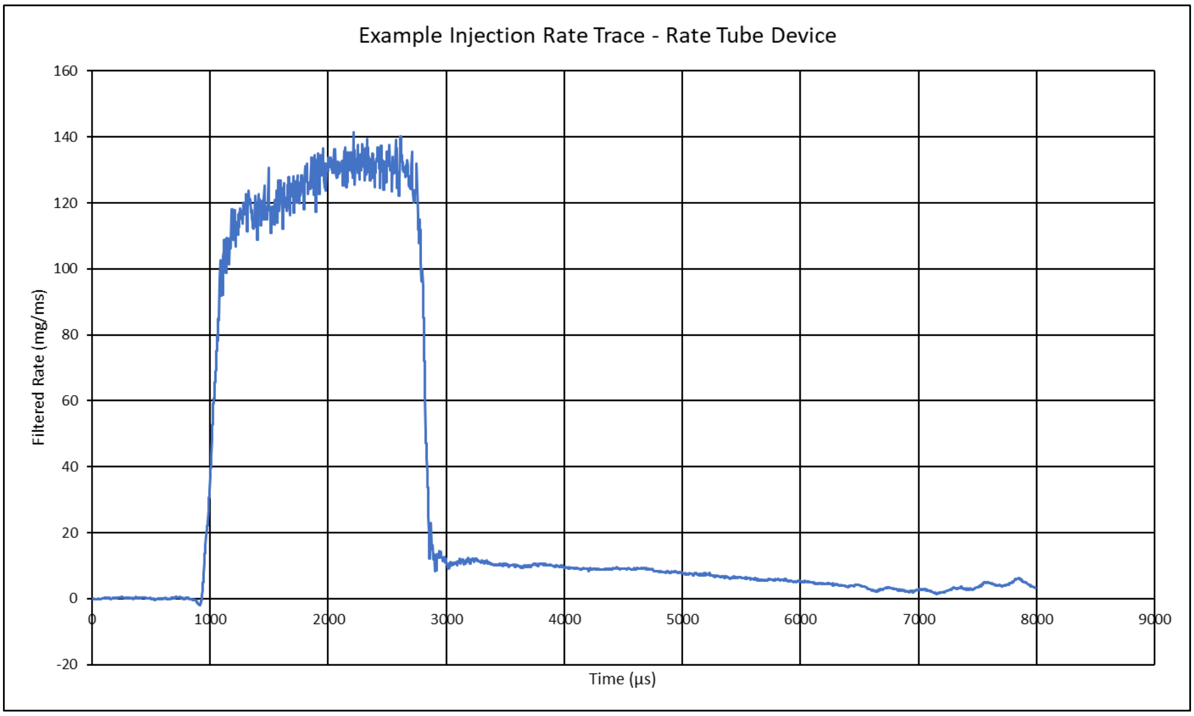

Figure 6 – Injection rate trace produces by a rate tube device showing thermally driven signal “float” at the end of injection.

Rate tube devices are limited by measurement errors caused by the temperature effects distorting the pressure signal, signal noise and pressure dynamics within the tube. The method had difficulties in achieving competitive cycle times for production application for two primary reasons. First, a period of consistent input into the device is required before measurement to limit the effect of a large temperature delta between the device and injected fluid. Secondly, time is required after each input into the system for the pressure in the tube to return to a state of quiescence before the next measurement cycle. The length of this period is directly linked to the length of the tube. The shorter the tube the faster the system will return to quiescence state which allows for a higher measurement frequency. However the longer the measurement tube is the greater the duration of injection the device can detect before the reflection begins to interact with the injection rate pressure trace.

Experiment Methodology

For this study each flow metering device was subjected to tests similar to Delphi Technologies' production style tests to benchmark device performance if it were to be used in a production application. Three development level DFi21 injectors were selected for these experiments with a range of nozzle flows (1.8, 2.0 and 2.2 litres per minute). The tests consisted of high resolution injection durations measurement sweeps which resulted in fuelings from 0.5mg to 220mg, at five different injection pressures, with a maximum pressure of 3000 bar as shown in Figure 7. Each injector was installed into a metering device and had the test plan repeated four times, with the results of the first test being omitted from the analysis. This process was repeated three times for each injector and the whole process repeated on each metering device. This paper will examine the results of the tests at 2500 bar due to the piston displacement device's limited ability to measure an injection pressure above that, with the 2.0 litres per minute flow injector. The tests completed with this injector showed the best measurement repeatability of the three used in the experiment and therefore should be the most accurate representation of the metering system's true repeatability. The performance of each of the metering device was evaluated on three main criteria; First the shot to shot standard deviation (SD) of the measurement, second the test to test standard deviation (SD) of the measurement and third the cycle time required to complete the production style test plan. A focused evaluation of the measurement performance at critical fuel deliveries will also be shown to highlight the effect accurate characterisation would have on engine performance.

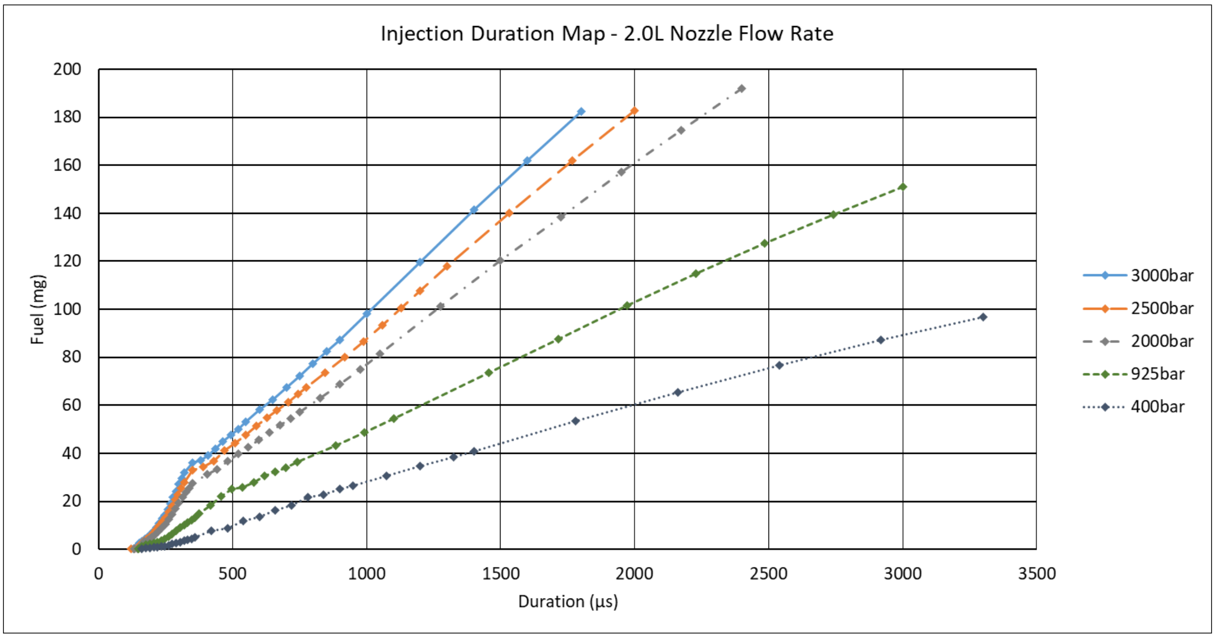

Figure 7 – The distribution of injection durations used in the measurement sweeps for these experiments.

Experiment Results

The shot to shot repeatability is a measure of the device's ability to accurately capture injections on successive injections and measurement cycles. Figure 8 shows the average standard deviation of the shot to shot measurement of the three metering devices across the nine test repetitions. It shows the three devices had comparable performance at all injection durations while the constant drain chamber device displayed a repeatability twice that of its competitors at long injection durations. Figure 9 shows the performance of the devices at important fuel deliveries. The piston displacement device and the chamber pressure device have noticeable increases in the standard deviation measure during different periods of the measurement sweep across the nine test repetitions - a feature which is absent from the rate tube device results. This device specific feature appears to coincide with the post injection quantity which could lead to a reduction in the accuracy of the characterisation of injector behaviour and a reduction in engine performance from injectors calibrated using this device.

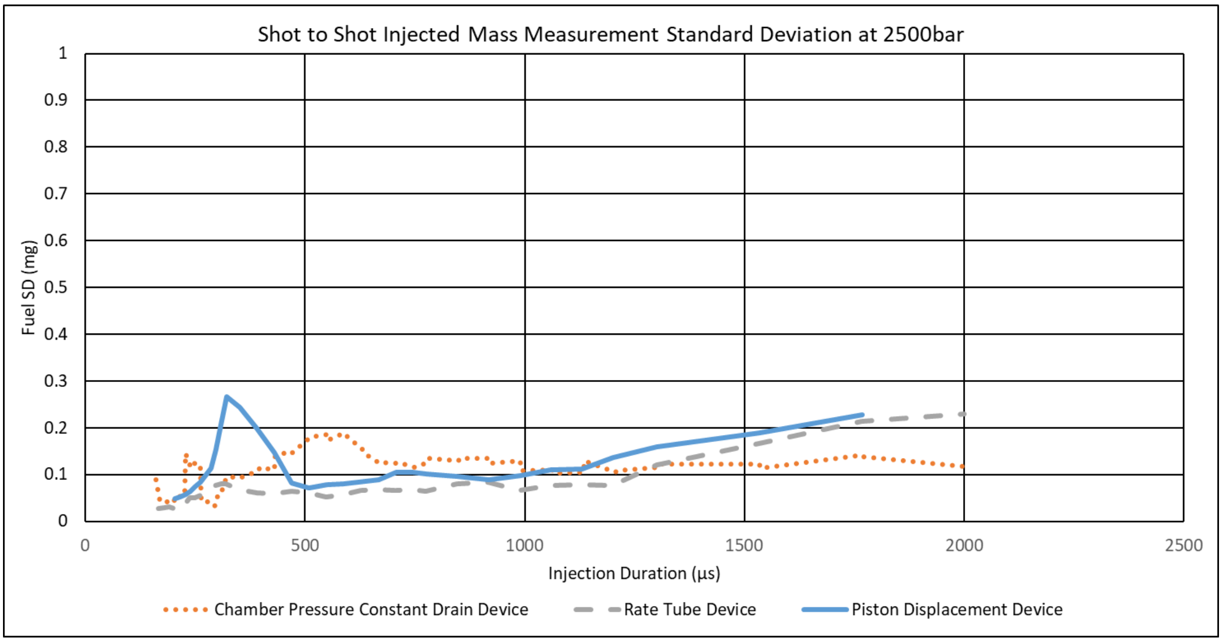

Figure 8 - The average shot to shot repeatability of the three metering devices during a measurement sweep at an injection pressure of 2500bar.

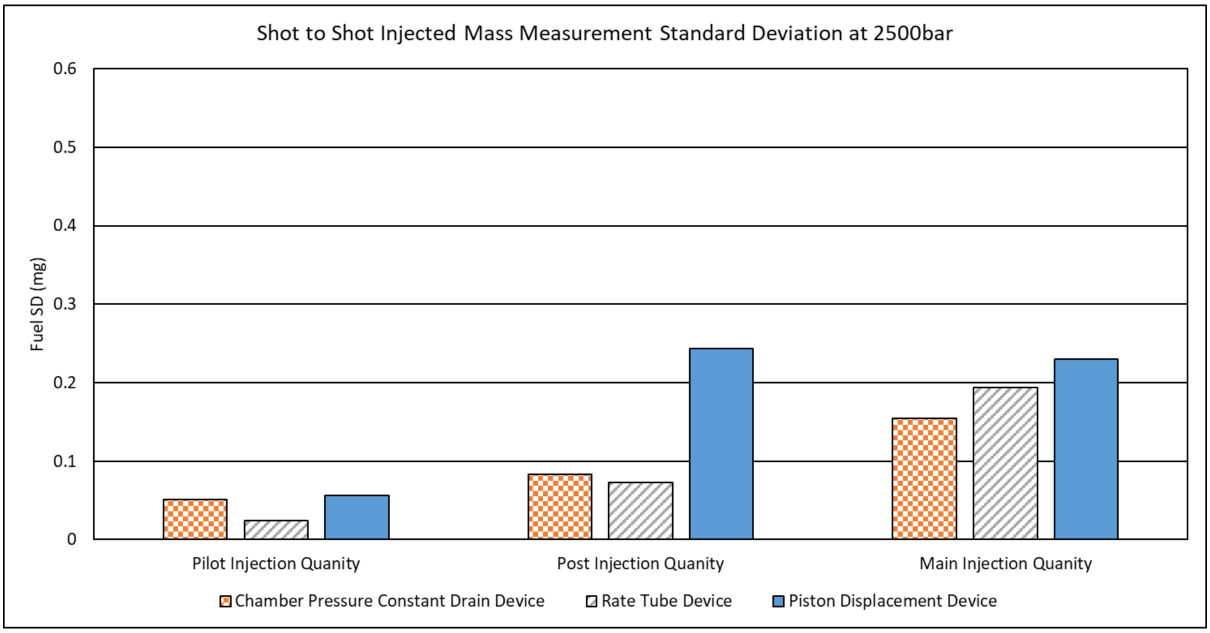

Figure 9 – The average shot to shot repeatability of the three metering devices at specific fuel deliveries of interest at an injection pressure of 2500bar.

The second evaluation method, test to test repeatability, is the ability of a metering device to characterise an injector on successive test cycles over the space of several minutes. Figure

10 shows the evaluation of the test data from the same tests the shot to shot data was taken from. The chart shows the piston displacement and chamber devices had a similar performance while the rate tube device was significantly less repeatable at the longer durations. Figure 11 highlights the lesser ability of the rate tube device to accurately repeat high delivery measurements over a period of minutes which could be caused by the inability of the device to return to the same hydraulic and thermal state. The period of injection drive signal and therefore the fuel quantity delivered, are changing during this period of the measurement sweep and can therefore cause a difference in temperature between the device the fluid. A rate tube can be vulnerable to this because of the thermal effects mentioned previously. An increase in the amount of time given for a consistent input to stabilise the system may have improved the measurement results but at the cost of cycle time.

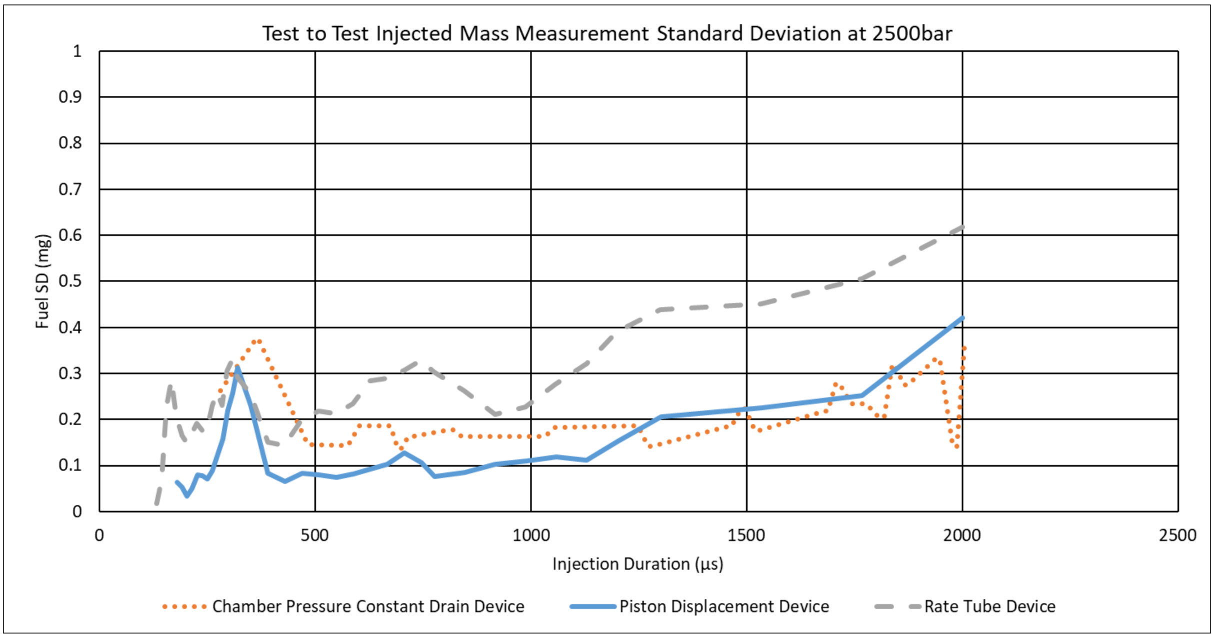

Figure 10 - The average test to test repeatability of the three metering devices during a measurement sweep at an injection pressure of 2500bar.

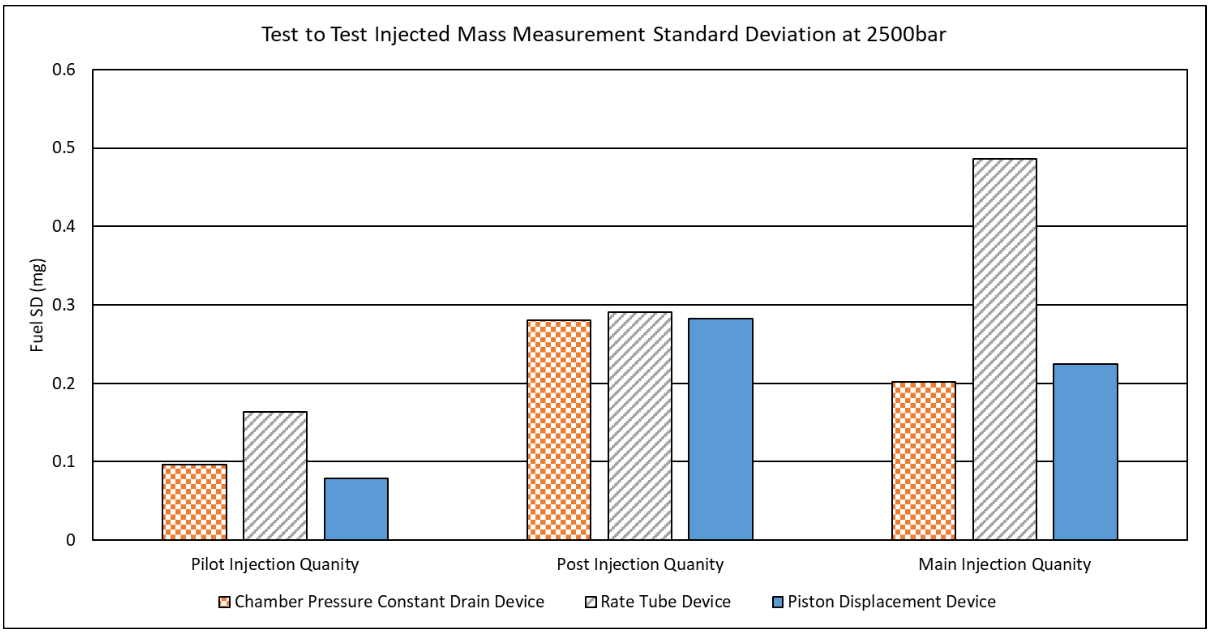

Figure 11 – The average test to test repeatability of the three metering devices at specific fuel deliveries of interest at an injection pressure of 2500bar.

The final method of evaluation is the time required for each device to achieve these results. A production environment demands accuracy and precision from a metering device but also requires that this level of measurement can be carried out in the shortest period of time possible. It is for this reason devices which utilise such methods as the gravimetric measurement and spray imaging [9] are impractical for use. The factors that drive cycle time are measurement frequency, the time required to stabilise the system before measurement and the number of shots required to accurately characterise performance. The time required for each system to complete the 2500bar measurement sweep in these benchmark tests is shown in Figure 12.

The piston displacement device displayed the best cycle time performance. The device is limited by the frequency at which the drain valve can return the chamber to a stabilised pressure but the device does not require a long period of wasted time stabilising before measurement. The constant drain device could achieve even greater measurement frequency but is limited by the maximum flow rate of its drain valve were the device used for higher flow applications this could affect the achievable cycle time. The limiting factor of the constant drain device in this study was the ability of the electronically controlled drain valve to maintain back pressure when quickly changing injection quantity. To mitigate this the resolution of the injection duration sweeps have to be increased which results in an increased cycle time. The time usually required to use the Coriolis meter was avoided in these experiments by using chamber temperature compensation, reducing the cycle time by 25%. The slowest device examined in this study was the rate tube device, due to the long periods of stabilisation required before measurement to ensure there was no significant delta in temperature between the device and the injected fuel. The pressure and flow requirements required for future applications could compound this effect further as injection energies increase. In addition a low measurement frequency is needed to allow the tube to reach an quiescence state after each measurement and this combined resulted in a doubling of the achieved cycle time when compared with the other devices in this study.

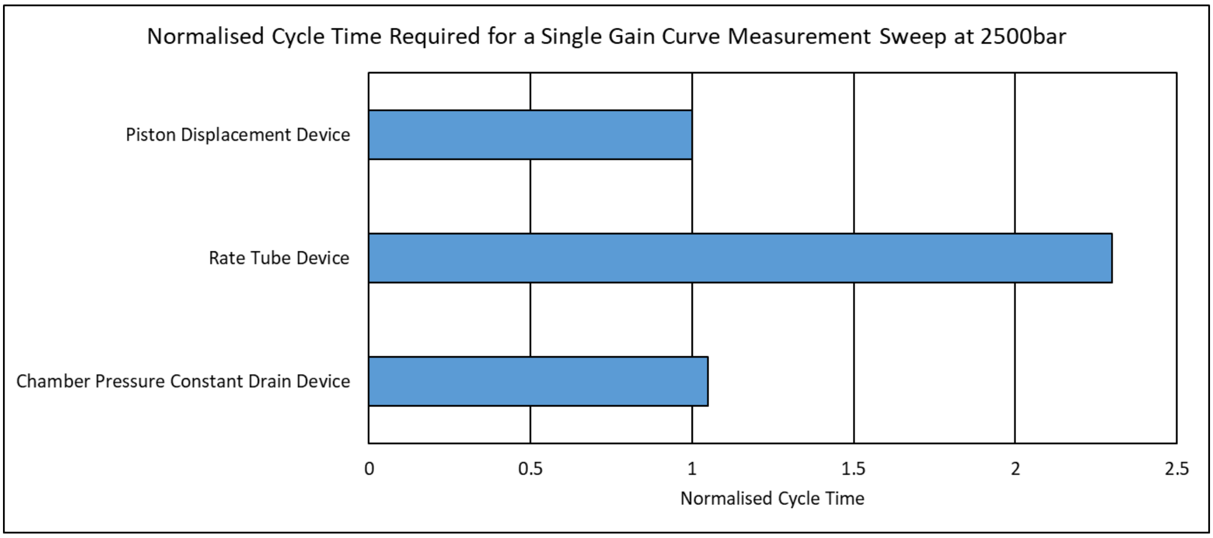

Figure 12 – Normalised cycle time for each device for a single measurement sweep.

Conclusion

On review of the three criteria outlined previously, no device clearly exceeded the others in all three criteria, although one device does have clear disadvantages against the other two. The shot to shot repeatability of all three systems is comparable, however the test to test repeatability of the rate tube device does not match that of the other two. This device also requires additional cycle time over the other two devices to achieve this level of repeatability making it prohibitively expensive for a mass production application.

The primary criteria for the evaluation of injection metering device performance are measurement repeatability and cycle time, however when deciding which device is suitable for a given application, factors beyond these should be also be considered. The benefit of rate tube devices first order injection rate is not as substantial if rate shape is no longer critical to injection strategies. Further the inability of the piston displacement method to accurately capture close coupled injections is an additional challenge for engineers working on those devices to overcome. The methodology and hardware of the chamber pressure constant drain device discussed in this study, when subjected to extreme injection pressures and quantities, is an unknown risk that must be explored if the device is to be successful.

Future powertrain solutions will require fuel system technology to advance beyond that used to meet the previous generation of emission standards and will continue to push the development of the equipment used to manufacture them. Greater injection pressure and flow, along with the characterisation of close coupled injections, are already pushing the capabilities of existing equipment to the limit.

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