**UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG**

**SCHOOL OF MECHANICAL, INDUSTRIAL AND AERONAUTICAL ENGINEERING**

# INVESTIGATION INTO THE RELATIONSHIP BETWEEN INJECTION PRESSURE, DURATION AND FREQUENCY IN COMMON-RAIL INJECTION SYSTEMS

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A research report submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, in partial fulfilment of the requirements for the degree of Masters in Engineering.

Johannesburg, 2015

# Declaration

**Name:** Jean-Paul Wilson **Student Number:** 0301592X

**Course No:** MECN 7018 **Course Name:** Research Report

**Report Title:** Investigation into the relationship between injection pressure, duration and frequency in common-rail injection systems.

I, **Jean-Paul Wilson** hereby declare the following:

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- This task has not been submitted before, either individually or jointly, for any course requirement, examination or degree at this or any other tertiary education institution;
- I have followed the required conventions in referencing the thoughts and ideas of others;
- I understand that the University of the Witwatersrand may take disciplinary action against me if it can be shown that this task is not my own unaided work or that I have failed to acknowledge the sources of the ideas or words in my writing in this task.

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# Abstract

This report investigates Common Rail Compression Ignition Engines, motivating for research on relationships between injection pressure, duration and frequency, and their effect on injector flow rates. The objectives were to investigate these relationships by means of both research and testing, employing the following methodology:

- Carry out a substantial review of the research and testing that has been done in this field.
- Develop the test rig and carry out tests.
- Analyse and interpret the results

The main findings from this research and testing included:

- Injection duration (under constant rail pressure and injection frequency) had no effect on the flow rate.
- Changes in the injection frequency did not produce any change in the flow rate.
- The flow rate fluctuated linearly with rail pressure. Injection duration and frequency were independent to each other, but further testing on this is required under different conditions.

These findings generally correlated well with previous research by others.

## Acknowledgements

The author wishes to acknowledge and thank Professor D. Cipolat for his leadership and guidance as a supervisor and Nicholas Rice for carrying out tests on which the analysis in this research is based.

# Contents

# List of Figures

# List of Tables

# Symbols and Nomenclature

| Symbol | Description | Units |
|---|---|---|
| A | Area of the injector orifice | $mm^2$ |
| A | Speed of sound in diesel | mm/s |
| $C_d$ | Discharge Coefficient | |
| $k_{1s}$ | Strain gauge amplifier gain | $kPa/cm^2$ |
| $k_{1p}$ | Charge amplifier gain | bar/V |
| N | Number of injector holes | |
| P | Pressure measured by strain gauge or pressure transducer | bar |
| $P_b$ | Back Pressure | Pa |
| $P_r$ | Rail Pressure | Pa |
| $\rho$ | Density of diesel | $kg/m^3$ |
| Q | Volumetric flow rate of fuel | $mm^3/ms$ |
| V | Voltage reading of strain gauge or pressure transducer | V |
| Σ | Conversion factor from $kPa/cm^2$ to bar | |
| CFD | Computation Fluid Dynamics | |
| CI | Compression Ignition | |
| CR | Common Rail | |
| DME | Di-Methyl Ether | |
| DC | Direct Current | |
| DT | Dwell Time | |
| EGR | Exhaust Gas Recirculation | |
| ET | Energising Time | |
| ECU | Electronic Control Unit | |

# 1 Introduction

## 1.1 Research Background and Context

### 1.1.1 Compression Ignition Engine Development

There are two main categories of internal combustion engines, namely compression ignition (CI) engines (that run predominantly on diesel fuel) and spark ignition engines (that run predominantly on petroleum). The focus of this research is based on compression ignition engines. The diesel engine was invented in 1897 by Rudolf Diesel, and, in many ways, it resembled the setup of most diesel engines in use today [1]. Traditionally, automobiles made use of spark ignition engines; however, diesel engines are continually increasing their market share of private automobiles. This is in part due to their high compression ratios which afford them lower fuel-to-air stoichiometric ratios, making them more fuel efficient than spark ignition engines. In addition, they do not require an electric ignition system, making their design simpler and more reliable [1].

Currently, diesel fuel is "the most important fuel currently in use worldwide, with the highest production rate of any fuel from oil" [1]. One of the reasons for this is that diesel engines are used in, among other applications, automobiles, buses, trucks, farm equipment, rail locomotives, yachts, pumps, compressors and generators. Improving their performance is therefore of major importance.

### 1.1.2 Engine Performance Overview

Fuel delivery systems have a major impact on the performance of the internal combustion (IC) engines on which they work. Therefore, the development of these systems has been ongoing for as long as IC engines. Although carburetors were the main means of fuel delivery over the previous century, the method of direct fuel injection has been in use as early as 1890 [2] . Herbert Akroyd Stuart, the inventor of the hot bulb engine, pioneered the development of the first solid fuel injector, which works on the same principle as most diesel injection systems currently in use [2].

**Fuel Economy**

The performance of a diesel engine can be attributed to the following parameters [1]:

- Vehicle dynamics/ behaviour.

- Fuel quality.
- Engine efficiency.

However, engine efficiency is a general term that may represent a number of engine related efficiencies including [3]:

- Brake thermal efficiency.
- Volumetric efficiency.
- Indicated thermal efficiency.
- Relative efficiency

Although the above listed items are important in their respective applications for engine analysis and development, the third item, indicated thermal efficiency is the most important measure of an engine's fuel consumption. It is defined as the ratio between the heat energy supplied, and the useful work that is done [4]. This term correlates to fuel efficiency, which is the ratio of the amount of fuel consumed to the useful work done by the engine. However, it must be noted that this is not always the case; the concentration of oxygen in the air, or the effect of exhaust gas recirculation also affects the efficiency with which the engine converts the fuel into useful work. For example, the implementation of an EGR system adds tar inducing contaminants, reduces engine power and reduces fuel efficiency [5]. Therefore, for the purposes of clarity, the term "fuel economy" will replace "fuel efficiency" for the remainder of this report.

From this perspective, the performance of an engine is integrally related to the design and operation of its fuel injection system. That is, not only is it important that the fuel gets delivered to the engine cylinders, but also, the manner in which this is done, that influences fuel economy.

**Fuel Injection Systems [6], [7]**

The fuel injection system is responsible for both the timing of the delivery of fuel to the cylinder as well as the metering – the amount of fuel delivered to the cylinder for each engine stroke cycle. In addition to the timing and metering, the injection system should also ensure the following:

- *Optimum fuel* atomisation, because the smaller the droplets of fuel, the better the chance of them all participating in the combustion process.

- *Bulk mixing* of the fuel with the oxygen so that maximum combustion efficiency is achieved
- *Air utilization*, being the effective utilization of the fuel in the combustion chamber.

The above factors are important responsibilities of the injection system. There are various different types of fuel injection systems with the most prevalent being the common rail fuel injection system used in most diesel engines today. The common rail fuel injection system was developed by Vickers Ltd in 1913 and was first utilised in a commercial American diesel engine in 1919 by the Atlas Imperial Diesel Corporation [8]. Other systems include the unit injector injection system and the distributor pump injector system. However, their development has slowed in recent years. This is because, when assessing various factors such as the need for improved ride quality, more stringent vehicle emissions regulations and better fuel economy, the common rail system has various advantages as compared to the other systems. These advantages include [8]:

- Independence of fuel pressure from engine speed and load conditions. This means that the injection speed and duration can be controlled regardless of the specific running conditions, leading to better engine management and improved fuel economy.
- The presence of the common rail negates the need for the injection to be timed perfectly with the peak torque of the fuel pump, offering greater flexibility in terms of injection discharge.
- Lastly, low $NO_x$ emissions and lower noise are attributed to injection systems which have pilot injections, and because of their ability to carry out these pilot injections consistently regardless of the engine speed and load conditions, the common rail injection system ends up being quieter, with lower emissions.

Because of this, although inherent design, running conditions and fuel quality all impact the fuel economy of a direct injection IC common rail engine, many of the major factors have to do with the performance of the fuel injection system. The injection system is responsible for, among other operations:

- Determination of the injection spray pattern (by atomising and partially distributing the fuel inside the combustion chamber). This spray pattern affects the combustion characteristics, such as, the efficiency with which the chemical energy in the diesel is converted to kinetic energy that moves the piston downwards and drives the motor.

- The frequency, number and duration of injections.
- The number of fuel injectors as well as the number of holes per injector.
- The common rail pressure and temperature.

Many of the above listed parameters are important for efficiency because the stoichiometry changes with differing operating conditions. For example, on idle, the air-fuel mixture is generally at stoichiometric conditions, while during high revving, the mixture becomes richer in fuel [5].

## 1.2 Scope and Objectives

### 1.2.1 Scope

Given the growing importance of diesel engines [1], much research is being done to improve their performance. One large area of research is on the fuel injection systems of these engines and within this body of knowledge, there is the need to investigate the effect of various injection parameters on the rate at which fuel is injected.

Therefore the scope of this research is focussed on the testing and development of three of these parameters that affect the rate of fuel injection, and how they relate to each other. The three parameters are:

- Injection Pressure
- Injection Duration
- Injection Frequency

### 1.2.2 Objectives

The objectives of this research were to:

- Research the current body of knowledge regarding common rail fuel injection systems and the relationships between the factors affecting fuel injection.
- Research the flow metering methodologies available and the benefits and drawbacks of each.
- After researching the most effective flow metering methodologies employed, develop a test rig, building on the work of previous researchers.

- Verify, by means of testing with the rig, previous work and/or present new findings based on the relationships between the three parameters listed in the scope. This objective can be explicitly described as follows:
    - Record the flow rate of fuel through an electronic injector at varying:
        - Injection Pressures (by changing the common rail pressure)
        - Injection Durations (by means of the injector controller (InjectoBot) described in 3.2.2)
        - Injection Frequencies (by means of the injector controller (InjectoBot) described in 3.2.2)
- Analyse the results of the tests after processing and interpreting them in order to uncover the relationship between the three injection parameters.
- Compare the analysed results to research done by others.

# 2 Technical Overview

## 2.1 Common Rail Injection System

### 2.1.1 Overview

In the common rail injection system there are three piping systems, a low pressure system, a high pressure system and a leak system, also designed for low pressure. The low pressure system connects the fuel in the fuel tank, the subsequent fuel pre-filter and fuel filter, and the high pressure pump. The high pressure pump system connects the high pressure fuel pump to the common rail, and the common rail to the electronic injectors. The pressure exerted by the fuel and pump inside the common rail is extremely high, with some makes, such as 3rd generation Bosch common rails exceeding pressures of 2000 bar [9] . The leak back system recirculates fuel from the pressure control valve on the common rail as well as excess fuel from the injector, back to the fuel tank [10]. A representation of this system is seen in Figure 2-2 [11].

The common rail, also known as the accumulator when discussed specifically and not part of the fuel injection system, is where the fuel pumped under pressure collects before being distributed to the various injectors that are connected to it, via high pressure steel tubing. To indicate scale, typical volumetric fuel capacity for the accumulator ranges from 16-20 $cm^3$ for commercial automobiles. The pressure control valve regulates the pressure in the common rail, and is connected to the ECU, thereby adjusting the pressure as required. Typical engine idling pressure is between 300 – 400 bar while under certain load conditions, this pressure can rise above 2000 bar [10].

### 2.1.2 High Pressure Fuel Pump

The fuel pump is responsible for providing the high pressures in the accumulator that are required for the effective running of the common rail system. The pump is unique; the tolerances are very high, as are the strength and durability of the materials used, as can be seen in Figure 2-1 [12] which is included to show what it looks like. The pump is a positive displacement pump which is one of the reasons that such high pressures are developed so quickly. Fuel metering control valves are found within the pump, which are able to vary the amount of fuel that is pumped to the common rail. The main advantage of this being that the parasitic load from this motor is greatly reduced, especially under lower engine load conditions [10].

**Figure 2-1: Indicative Photograph of High Pressure Fuel Pump**

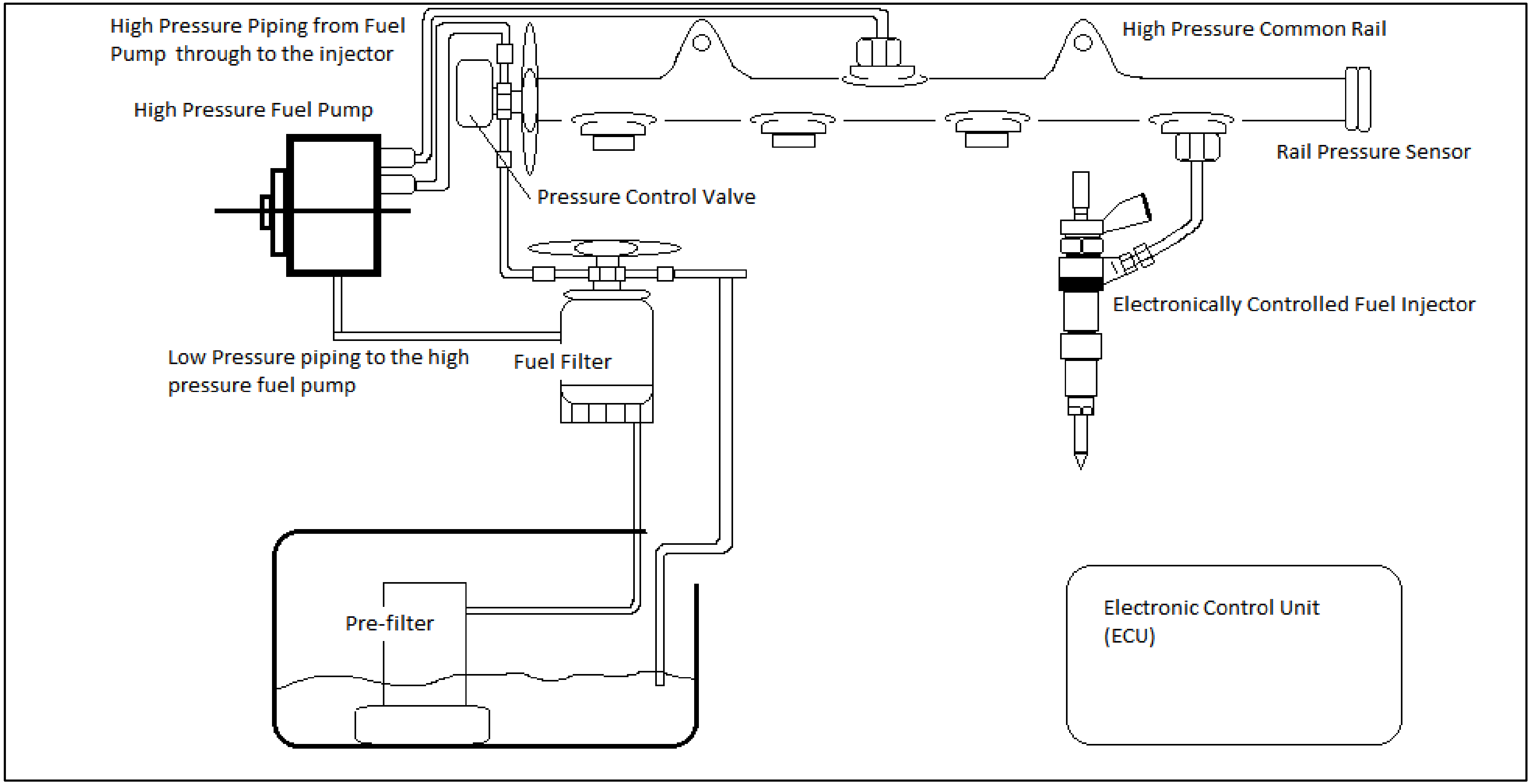


**Figure 2-2: Representative Figure showing the Common Rail Injection System**

### 2.1.3 Injector and ECU [10]

The fuel injector employs either a piezo-actuator or a solenoid that lifts and depresses, resulting in the injection of fuel into the combustion chamber, via the injector nozzle (see Figure 2-3 [13]). The latter is more common and is used in the experimentation carried out in this work. However, it must be noted that piezo-electric injectors are becoming more prevalent, mainly due to their faster mechanical response time when compared to solenoid actuator injectors (up to 4 times as fast). High pressure fuel is fed from the common rail and enters the injector via the high pressure fuel inlet. From here it enters both the needle seat area and the area below the injector needle piston. The fuel therefore does not affect the change in the position of the needle piston. This is done by the change in the electrical signal from the ECU. A voltage or an earth is supplied to the piston and this either energizes or de-energizes the piston, causing the movement of the needle piston, and effecting the start, continuation or end of the injection [10].

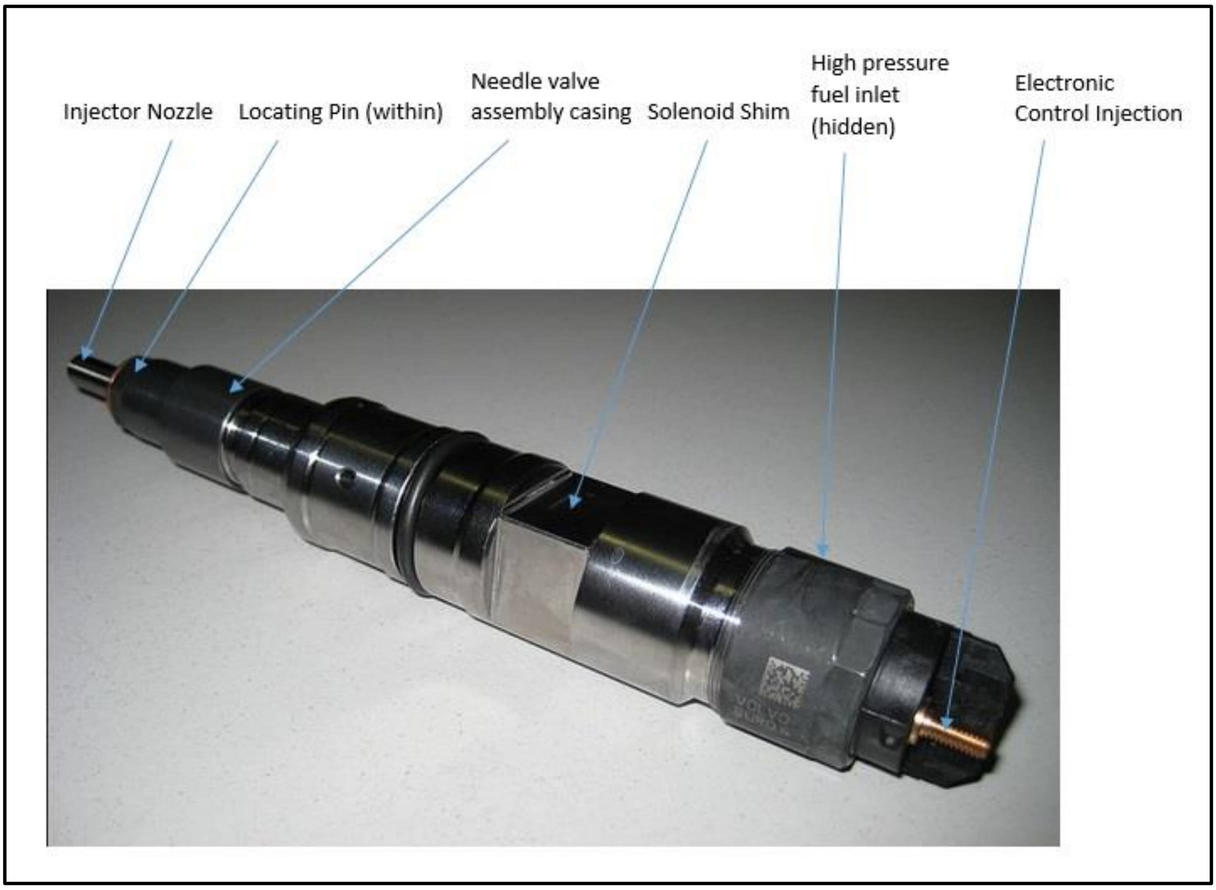


**Figure 2-3: Some Components of an Electronic Fuel Injector**

The electronic control unit is responsible for interpreting such inputs as the acceleration (throttle) and engine speed (camshaft rpm & camshaft rpm) and outputs such as the rail pressure, fuel pump speed and injection behaviour (including injection frequency and duration). It carries out several thousand computations per second and operates on a closed loop system. An explanatory flow diagram demonstrating this closed loop control cycle is provided in Figure 2-4 [14].

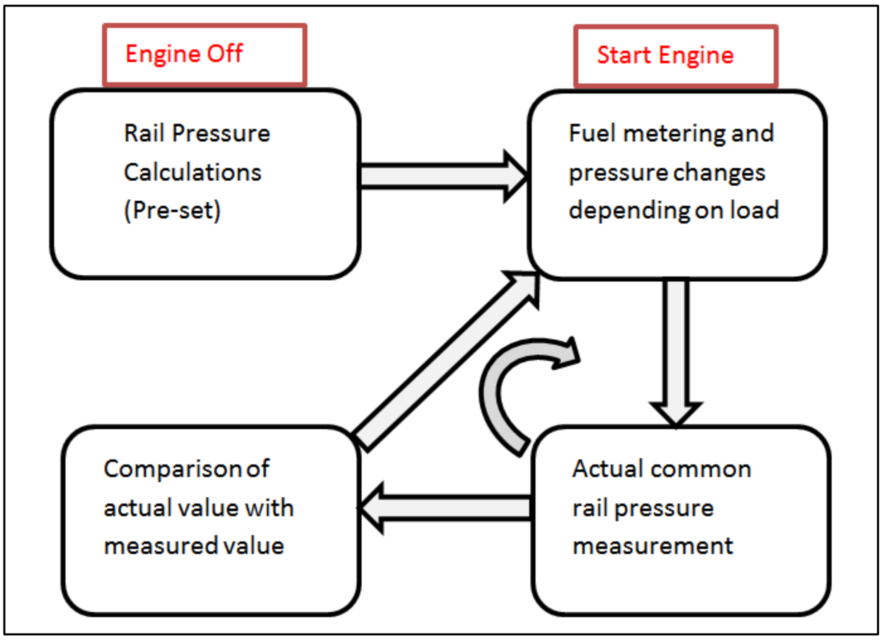


**Figure 2-4: ECU Control Cycle Flow Diagram**

## 2.2 Flow Metering

In order to continually improve the fuel economy of the CR engine, an accurate means of determining fuel consumption is required. However, in this application, measuring the fuel flow rate is relatively complex and therefore difficult to achieve, given that:

- The operating temperatures of IC engines are very high, making it unsuitable for placement of metering instrumentation in many instances.
- There are many parts that move at high velocities (piston, injector needle, fuel pump, etc.)
- The amount injected is very small.
- The frequency of injections is very high.
- There is no access to the combustion chamber into which the fuel is injected.

In addition to the above listed factors, the most important reason for the measurement of flow being complex has to do with varying “injection characteristics”. These are defined as a plot of the fuel flow through an injector (generally measured in cubic millimeters) against either time, or crankshaft angle [15]. With modern engines, the injection characteristics vary substantially with different load conditions. If this was not the case, the fuel could be metered by simply recording the loss of fuel over a certain period of time calculating the consumption of fuel from a fuel tank, and dividing this by the number of injections that took place. This not being the case is the motivation for the research (on the metering of fuel flow rates through common rail injection systems) that has been done, and for the research that is still required.

### 2.2.1 Classical Methods

Rotate calibrate and stroboscopic methods divided the crankshaft cycle into sections and collected individual injections in separate beakers. However, these were very inaccurate methods as fuel was lost to evaporation from overspray, and the inertia of the equipment required engine rotational speeds far slower than engines actually operate (for example, a maximum of 1000 rpm) [15].

As an aside, the use of imaging techniques (such as Schlieren, shadowgraph, direct photography, etc.) is very useful for research related to the injection spray analysis, however, not the metering of these injections. For spray pattern analysis, it is required that the injected fuel is observed. Therefore the combustion chamber is replaced with a chamber that has transparent casing (in most instances, this is glass).

Another method that was developed involved measurement of the electrical charges from the sprayed fuel - which could be used to calculate the flow. Unfortunately, because of the extremely low strength of the electrical signal, the technique was susceptible to external disturbances and was therefore never practically applied [15].

In 1961, Zeuch [15] published research detailing a proposed method of flow metering that measured the piston speed as it was displaced during the power stroke after injection of fuel. Marcic [16] developed another technique based on the same principles and published results that were more accurate than Zeuch’s. However the method employed by both Zeuch and Marcic, as with the other methods listed, is impossible to calibrate without calibration procedures that involve uniformity of the injection volume for several hundred engine strokes. Because of the variation in each injection, this is not possible. For these reasons a new, more accurate method was required.

### 2.2.2 Computational Modelling

With the advent of CFD, modelling of fluid flow has become a useful technique in many applications where empirical methods are not practical (or cost effective). In diesel engine spray modelling, CFD has been used since the mid-1970s [17].

CFD modelling on injector sprays generally makes use of one of two mathematical models, namely the Continuum Eulerian or Discrete Langragian models. Although the majority of the work done with CFD has more to do with spray propagation, looking to determine the way in which the spray mixes with the air in the chamber to develop the correct spray for optimum combustion efficiency, CFD has also been employed to understand the amount of fuel flow through the injector, given the common rail pressure. [17]

### 2.2.3 Impulse-Momentum Method [15]

**Description and Methodology**

The method of flow metering proposed by Bosch makes use of the effects of pressure pulses. This phenomenon is used in various other applications, albeit identified by other names. For example, it is used for measuring the flow of fluid through pipes and casings in the oil and gas industry. The principle is implemented with the water-hammer, or Joukowsky equation [18]. That is, pressure pulses (caused by the injection of fuel from the injector) propagate through a fluid medium (the fuel being injected) at the speed of sound in that medium and they effect a pressure change which, when the fluid they are travelling through has a velocity, effects a corresponding change in velocity. Therefore, if a means of determining the magnitude of the pressure pulse caused by the injection of fuel is known, the velocity of the fuel can be calculated. Then, as the diameter of the injector holes in the nozzle through which the fuel flows are known, the flow rate can be calculated.

The means for determining the magnitude of the pressure pulse that was employed by Bosch was a strain gauge. However, a pressure transducer could similarly be used, and in the rig developed at the University of the Witwatersrand from 2007 onwards, both a strain gauge and a pressure transducer are made use of.

This method makes use of the following relationships (1) to (4) below [15]:

$$P = \varsigma k_{1s} V \quad \text{and} \quad P = \varsigma k_{1p} V \qquad \textbf{(1)}$$

$$Q = \frac{PA}{a\rho} \qquad \textbf{(2)}$$

Where,

P = Pressure Measured by Sensor (Strain Gauge or Pressure Transducer) [bar].

$k_{1s}$ = Strain Gauge Amplifier Gain [kPa/cm$^2$].

$k_{1p}$ = Charge Amplifier Gain [bar/V].

ς = Conversion Factor from kPa/cm$^2$ to bar..

V = Voltage of either the Strain Gauge or the Pressure Transducer [V].

Q = Volumetric Flow Rate of Fuel [mm$^3$/ms].

A = Flow Area [mm$^2$].

a = Speed of Sound in Diesel [mm/s].

ρ = Density of Diesel [g/mm$^3$].

For the theoretical calculation of the flow rate, the following expression is made use of:

$$Q = NC_d A\sqrt{\frac{2P}{\rho}} \qquad \textbf{(3)}$$

Where,

N = Number of Injector Holes.

$C_d$= Discharge Coefficient.

A= Area of the Injector Orifice [mm$^2$].

P= Pressure Difference [Pa].

$P_b$= Back Pressure [Pa].

$P_r$= Rail Pressure [Pa].

ρ= Density of Diesel [kg/m$^3$].

The pressure difference is calculated using:

$$P = 0.9P_r - P_b \quad \textbf{(4)}$$

This method is the most effective available and is the method used in the research and testing described in this report.

# 3 Current Developments

The subsequent sections of this report address the scope and objectives of the research. That is, they describe what has been previously done by others, as well as the testing, analysis and interpretation in this work and how it all contributes to the understanding of how the various fuel injection parameters affect the flow rate and each other.

## 3.1 Research Development

### 3.1.1 Experimentation

**Single Injection**

In individual injection experimentation, the behaviour of the fuel flowing through the injector is different to that for multiple injections. The reasons for this have to do with the interaction of the consecutive injections between each other during multiple injections. However, the injection process is still the same and therefore, understanding the isolated injection itself is still vitally important for this work. Injection tests measuring the fuel flow rate, rail pressure and injector inlet pressure indicate that, after an injection [19]:

- The common rail pressure drops considerably (by approximately 50 bar gauge in the tests conducted).
- The injector is delayed and therefore takes longer to inject than the time taken for the current signal to be sent to the injector.
- There is a pressure drop at the injector inlet immediately after the injection, which is a result of the pressure wave caused by the injection.

**Multiple Injections - Pilot Injection**

The main area of interest would be multiple injections, where the effect of the interaction between the injections is taken into account. The first interaction of importance is between the pilot injection and the subsequent injections, with the first having different behaviour to the subsequent injections. The reason for the difference in behaviour is that the pilot injection occurs when the common rail is fully charged.

It has been found that the injector controller signal is not the only factor affecting the duration of the injection of fuel. The pressure in the fuel (that is, the pressure in the common rail) affects the speed at which the solenoid returns to the closed position within the injector. So, even though the signal from the controller may have cut the current to the solenoid, the higher pressure in the rail during the pilot injection means that more fuel is injected [19].

### Fusion and Dwell Time

The high speeds and frequencies of fuel injection mean that, as alluded to in the discussion on the pilot injection, there is a lag between the point in time at which the injector controller sends the current signal to the injector, and the point in time at which the solenoid attached to the injector needle is charged, causing the opening or closing of the injector. This lag is known as the dwell time. It is an important concept as it affects the manner in which the injections change the flow rate of the fuel. At very high injection frequencies, the dwell time can become a longer period of time than the time between injections. At this point there is little/ no distinction between injections and this is known as fusion.

Investigations were carried out by Catania, et al [20] to better understand how the nozzle opening and closing, current delivery to solenoid, energizing time, and CR pressure related to each other and influenced the occurrence of fusion. A mathematical model (that they developed in earlier work, and described above) was also used to better understand these interactions. The model comprised of a thermodynamics fluid model, and a mechanical and electrical sub model.

The findings of their research that are of most value to the current research include:

- There is a direct correlation between dwell time and injection flow rate. When the dwell time between two consecutive injections (regardless of whether they are pilot, main or post injections) is varied, the pressure oscillations from the first injection cause an uncontrolled fluctuation in the volume injected in the following injection.
- Shorter injection pipes with larger internal diameters reduce the amplitude of the injection oscillations.
- The main factor contributing to the occurrence of fusion in consecutive injections is the delay that occurs between the electrical signal being sent to the solenoid of the fuel injector and the actual lifting of the injector needle, allowing the fuel to flow through.
- The delay between the sending of the current signal and the lifting of the needle within the solenoid is related to the pressure in the common rail that is transferred along the injection path to the injector needle/solenoid. This force needs to be overcome. That is, when the pressure is high, the force required to induce movement in the solenoid is high.

In addition to the dwell time affecting the likelihood of fusion occurring, it was also found that nozzle closure delay also contributed to fusion. Using the numerical model to determine the flow rates, needle lifts and mass flow rates through various injection hole types, it was found that the needle dynamics was a contributing factor. In turn, the needle dynamics are related to the injector hole types and configurations.

**Injection Pressure, Speed and Duration - Flow Rate Relationship**

When looking at previous work done specifically investigating the relationship between the flow rate and three parameters that this research aims to gain insight on, work carried out by Khan [21] found the following behaviour:

- Increasing the rail pressure causes an increase in the injection flow rate.
- Increasing the rail pressure causes an increase in the energising time (attributed to the slower rate of closing of the injector solenoid [19] ).
- Increasing the injection duration increases the flow rate.
- Injection frequency has no effect on the flow rate of the fuel.

In addition, this was corroborated by Watkins [22] where it was found that the flow rate increases linearly with increasing injection pressure.

### 3.1.2 Modelling

As the hydraulic behaviour within the injector and common rail become better understood, more research is being done with computer models, instead of physical experimentation. However, this is not a fully developed practice in the area of common rail engine flow rate optimisation and therefore requires substantial research and refining. The following describes the findings of the mathematical models that have been used, in order to highlight the areas of difference with experimental work, thereby guiding the focus of said experimental work.

Research conducted by Seykens et al [23] made use of AMESim simulation software to model the injection process in a common rail system. Specifically, it was possible to accurately model the injection rate, needle lift and the injection pressure. The accuracy was determined by carrying out testing on a common rail, high pressure pump, and injector under identical conditions and comparing the results. Although the results of the comparison between the model and the testing were favourable, it was found that both the discharge coefficient and the elasticity for the injector needle assembly (spring constant) found in literature vary too widely for accurate results. Therefore, in order to obtain accurate modelling, it is required that the discharge coefficients and the injector needle assembly elasticity be tuned by testing, before making use of modelling.

In addition to hydraulic modelling discussed, work has also been done with regard to mechanical, electromagnetic and mass flow models [24]. All of these models would be useful in obtaining more insight into various parts of the injection – flow rate relationship.

## 3.2 Rig Development

The metering of fuel through the injector is integral to the research on injection pressure, duration and frequency. Therefore, as it was found to be the most effective metering method available, a rig making use of Bosch's impulse-momentum method was built and developed (by various students, including myself) at the University of the Witwatersrand, Johannesburg.

### 3.2.1 Initial Design and Construction

The first iteration of the test rig replicating the Bosch method of fuel injection was built by Huber in 2007 [25]. Although based on it, the rig was different from the one constructed by Bosch, with reasons including the improvement in construction methods and materials, and the need to accommodate both mechanical and electronic injectors. Once designed and constructed, tests were carried out successfully, observing injection pulses with an oscilloscope.

### 3.2.2 Implementation of an Injection Controller

As all modern fuel CI engines make use of electronically controlled injectors, it followed that the testing should be done with such injectors. This required the purchase/ design and construction of an injector control unit. In 2009 Mclean [26] designed and constructed several such devices. McLean called the electronic fuel injector the "InjectoBot" and it is referred to in this report as such.

The work done by McLean had the aim of designing, constructing and testing a controller for electronic fuel injectors. The controller was planned for use in various tests relating to fuel flow rate measurement and fuel injection spray pattern analysis.

The project focussed on the design of an electronic circuit that would send a signal to the fuel injector, thereby controlling the movement of the solenoid within, which in turn regulates the flow of fuel through the injector. The controller would allow the injector to operate at a range of injection frequencies and durations (referred to in McLean's report as the pulse width, measured in milliseconds).

One of the initial, major considerations was whether to make the controller analogue or digital in its design and operation. A decision table was generated to compare the various characteristics of each methodology. An analogue circuit design was selected with some of the reasons including:

- Lower cost.
- Ability to modify.
- Ability to repair.
- Portability.
- No need for a computer to interface with the controller.

**Functionality:**

The undertaken design philosophy divided the controller into three main sections. That is, two integrated circuits and a pair of independent variable resistors, or potentiometers.

Both the voltage frequency and the pulse width would be generated by an integrated circuit called a 555 timer. The setup of the 555 timer would provide for an astable circuit, whereby using a capacitor, the charge would fluctuate between 1/3 and 2/3 of the voltage of the supply.

The voltage magnitude for both the frequency and the pulse width generated by the 555 timer would be set using the potentiometers. As they are independent of each other, the frequency may be adjusted while leaving the pulse width unchanged, and vice versa.

The signal generated by the 555 timer would not be sufficient to charge the solenoid. It therefore required amplification. This was done by the second IC, a MOSFET which, like the 555 timer is a low-cost, off-the-shelf item.

Additional components were required for protection of the two ICs. The controller may be switched off after energising the solenoid in the injector (that is, lifted off its seat in its open position) and therefore the charge left in the injector would need to be discharged. However it is far higher than the 555 timer can accommodate and therefore a diode is placed between the two circuits to prevent the discharge into the 555 timer, and damaging it. Additionally, the circuit is DC and therefore cannot handle the reverse flow of charge regardless of the 555 timer. This is the other reason for the placement of diodes within the circuit.

A heat sink is also placed next to the MOSFET as, with the high current flowing through it, the possibility of it overheating exists. Other components included LEDs for indicative purposes (red and blue LEDs indicating power and injection signals) and capacitors to reduce noise (propagated as inductance via the long wires from the power source and the injector).

After completion of the design of the circuit, it was then constructed. It was tested using a data logging card, and the results were processed in MATLAB. These processed results were then output to a csv file so that graphs depicting the ranges for both the frequency and pulse width could be plotted. The ranges found were as follows:

- **Frequency:** 0.3 – 15.38 Hz.
- **Pulse-width:** 3.2 – 6.4ms.

The author states that there is a difference in the control voltage and current for each injector, meaning that the system would have to be calibrated for each injector. This statement is of concern as there is no method provided for modifying the injector controller based on these differences. It also seems unlikely that an injector manufacturer would allow such variance in a standardized product. It may be that what is meant is that the voltage and current requirements vary for each injector type and model – meaning that calibration of the controller to each fuel injector is required.

The injection control unit was successfully designed, constructed and commissioned, and incorporated into the rig. It is a reliable method for controlling injectors for use in tests relating to spray pattern analysis and fuel flow rate measurement

### 3.2.3 Further Modifications

Subsequent to the design and construction of the injector controller, the test rig could then accommodate electronic fuel injectors. In 2009 Khan [21] further modified the rig by:

- Incorporating a pressure transducer along the measuring tube, thereby allowing for two separate methods of measuring the magnitude of the injection pulse. This is useful for verification of results.
- Implementing a data logging system for the recording of data at different injection settings for analysis.

During the 2$^{nd}$ round of testing, after multiple attempts, the data logger that had previously been used was assumed to be not recording as required, and so an alternative data logger was used. (CoCo – 80 Crystal Instruments Handheld Data Logger).The motivation for the change in the type of data logger was that it was unclear if the lack of accurate readings was solely due to the high level of vibration in the system and the data logger was suspected of being faulty.

The undergraduate student, Rice [27], who carried out the third round of testing added significant damping material to the test rig with the intention of improving the amount of vibration within the system.

The work I carried out in preparing the test rig for the experimentation is described in Appendix 2.

# 4 Experimental Setup

## 4.1 Rig Description

The objectives described in 1.2.2 require a rig that:

- Measures the rate of fuel flow through the injector (using the impulse-momentum method developed by Wilhelm Bosch) [15].
- Allows for varying injection pressure and duration and frequency.
- A data logging system to record the injections and calculate the flow rates .

All of these requirements are fulfilled and described in Section 3.2. However, the detail of the equipment and instrumentation made use of is now described.

### 4.1.1 Setup and Operating Philosophy

The rig required for the testing can be conceptually divided into two sections. The fuel delivery system and the fuel metering system. The former is similar to the actual set up in a CI engine vehicle while the latter is the impulse-momentum metering system previously described.

A fuel sump stores diesel fuel. This fuel is pumped from the sump by means of a high pressure fuel pump into the common rail. The pump is powered by a 3 phase motor. The common rail has its pressure regulated by a pressure transducer located on its one end (see Figure 2-2: Representative Figure showing the Common Rail Injection System). A multimeter measures the voltage on the pressure transducer, allowing for variation of the pressure in the common rail. The common rail is connected via high pressure steel tubing to an electronic injector. The other connections on the common rail are blocked off as only one injector is being used for the testing. This injector is connected to the InjectoBot injector controller which has analogue controls for both the injection duration and frequency. The injector is located in an aluminium injector housing to hold it in position during operation. In addition, the injector housing holds the strain gauge used for measuring the magnitude of the shock wave caused by the injection of fuel.

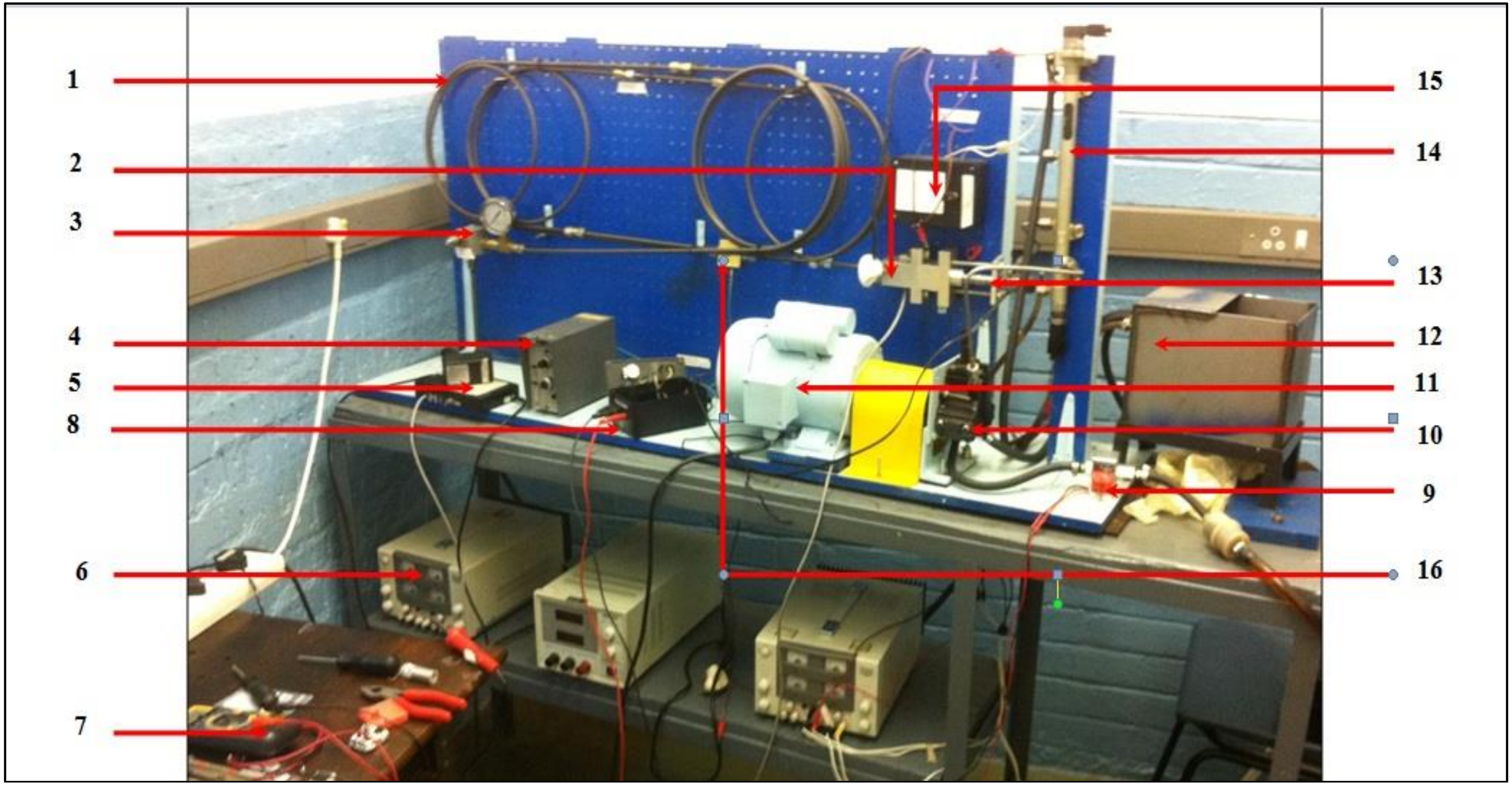


**Figure 4-1: Test Rig with Equipment and Instrumentation**

The injector nozzle fits into the measuring tube, which is a long section of steel tubing into which the fuel is injected. From the measuring tube, the fuel is fed back into the fuel sump. Along the measuring tube, the pressure transducer is located. This allows for a secondary method of measuring the magnitude of the shockwave from the injection of fuel, and therefore the fuel flow rate. The measuring tube has two sets of circular bends in it. The purpose of these is to allow the shock from each injection of fuel to be dissipated, thereby preventing a build-up of vibration in the in the apparatus which would make it difficult to differentiate between the individual fuel injections.

The rig has two amplifiers, one for the strain gauge and one for the pressure transducer. These are both connected to a data logger so that the voltages that they record can be stored, for data processing to determine the flow rate, at the completion of the testing.

### 4.1.2 Equipment and Instrumentation

Table 4-1 and Table 4-2 below, together with Figure 4-1 depicting the rig, describe what was used for the generation of the data that was analysed.

**Table 4-1: List of Test Rig Instrumentation**

| | Name | Specifications |
|---|---|---|
| 2 | Strain Gauge (inside injec-tor housing) | Strain gauge constructed by Louis Eder |
| 4 | Charge amplifier | **Make**: KISTLER Instrumente AG<br>**Serial Number**: 28338 **Part:** Type 5001 |
| 5 | Strain Gauge Amplifier | **Make:** MTC **Range:** VMD 35 |
| 7 | Multimeter | **Make:** Craftsman **Type:** Digital Multimeter 82141 |
| 16 | Pressure Transducer | **Make:** AVL **Part:** 5QP2002<br>**Measuring Range:** 0 to 600 bar, 6.2pC/bar |
| N/A | Data Acquisition System for test test 2 | **Make:** Crystal Instruments<br>**Model:** CoCo – 80 Handheld Data Recorder, Dynamic Signal Analyzer &Vibration Data Collector |
| N/A | Pressure Gauge | **Make:** Melco **Range:** 0-10 MPa |
| N/A | Rail Pressure Sensor | **Make:** Bosch **Voltage:** 5V |
| N/A | Data Acquisition System for test set 1 and 3 | GraphTec Hard Disk Logger GL 1000 |
| N/A | Laptop | **Make:** HP **OS:** Windows XP |

Table 4-2: List of Test Rig Equipment

| | Name | Specifications |
|---|---|---|
| 1 | Fuel Rate Indicator | Constructed with Carbon Steel & Aluminium by D. Huber, 2007 |
| 3 | Pressure Relief Valve | **Make:** MTC **Range:** VMD 35 |
| 6 | Power Supply | **Make:** Topward **Model:** Dual-Tracking Power Supply 6306A<br>**Range:** 0-30V |
| 8 | Injector Controller | **Make:** Made by Student B. McLean<br>**Type:** Analogue with potentiometers for injection duration and frequency variation |
| 9 | Low Pressure Fuel Pump | **Make:** Facet **Model:** Cube **Type:** Solid State Fuel Pump<br>**Max Pumping Head:** 2133.6mm |
| 10 | High Pressure Fuel Pump | **Make:** Bosch **Part:** 0445010024 **Engine:** A6110700701<br>**Type:** Piston Pump |
| 11 | Pump Motor | **Make:** Femco **Power:** 0.75kW **Speed:** 1440rpm<br>**Number of Phases:** 1 **Type:** Induction (Capacitor) TECCM16100 |
| 12 | Fuel Tank | Designed and Constructed in the North West Engineering Lab, Carbon Steel |
| 13 | Electronic Fuel Injector | **Make:** Bosch **Part:** A 611 070 12 87 **Hole size:** 0.241mm<br>**Number of holes:** 6 |
| 14 | Accumulator Common Rail | **Make:** Bosch **Part:** 0445214004 **Engine:** A6110700095<br>**Maximum Pressure:** 1800bar |
| 15 | Rail Pressure Control Unit | **Make:** Constructed by Wits University<br>**Range:** 272 - 560 bar |
| N/A | Rail Pressure Valve | **Make:** Bosch **Voltage:** 10V **Model:** A 611 070 00 95 |
| N/A | Automotive Battery | **Make:** Willard **Model:** D00404201180E<br>**Supply:** 12V, 60Ah, 350A |

## 4.2 Methodology

### 4.2.1 Overview

The manner in which the testing was conducted had the aim of uncovering how the three parameters (injection pressure, duration and frequency) affect each other, and the flow rate of fuel through the injector. Therefore, series of tests were run with one of the parameters being altered while the other two remained constant. For example, the injection pressure in the common rail would be kept constant and so would the injection duration for a series of tests, and the injection frequency would be changed for each of these tests. This way, the effect of the injection frequency on the flow rate could be uncovered. This would be done with all three parameters.

The methodology is an iterative one, with the test rig and its development requiring consideration during the testing. For this reason, although this methodology is the intended way of testing, the initial tests may not follow this (for example, in the initial round of testing, only one of the tests were successful, and so the full range of tests were not carried out, but one of the tests were useful and insight was drawn from it – test run 4).

The nature of the test itself would be to allow the recording of data from the strain gauge and pressure transducer onto the data logger for several injections (5 – 25 injections – the specific number not being relevant). This information was then processed to calculate the flow rate with the intent of gaining insight into the relationship between these factors.

The details of the test parameters are as described in Table 4-3: Description of Tests and Parameters for Each. To illustrate, at rail pressure 300bar, there are three tests with an injection frequency of 3.2ms (0.58, 1, 15Hz), three tests at 5.2ms, and three tests at 6.4ms. This is the same for each of the rail pressures in Table 4-3: Description of Tests and Parameters for Each Test giving a total number of tests of 54.

**Table 4-3: Description of Tests and Parameters for Each Test**

| Rail Pressure (bar) | Injection Duration (ms) | Injection Frequency (Hz) |
|---|---|---|
| 300 | 3.2, 5.2, 6.4 | 0.58, 1, 15 |
| 350 | 3.2, 5.2, 6.4 | 0.58, 1, 15 |
| 400 | 3.2, 5.2, 6.4 | 0.58, 1, 15 |
| 450 | 3.2, 5.2, 6.4 | 0.58, 1, 15 |
| 500 | 3.2, 5.2, 6.4 | 0.58, 1, 15 |
| 550 | 3.2, 5.2, 6.4 | 0.58, 1, 15 |

### 4.2.2 Testing - Precautions

During the set up and running of the tests, the following was adhered to:

- Ensure safety goggles are worn by all in the test room while the induction motor is running.
- Ensure the fuel lines and their connections are in working order, thereby preventing leaks when correctly fastened.
- Ensure that the extractor fan is running while the rig is, and for a considerable time after, in order to rid the room of fuel vapour.
- Exercise care when handling the section of the fuel rate indicator where the strain gauge is located, as this is easily damaged, and has been in the past, delaying the running of tests.

### 4.2.3 Testing - Rig Preparation

Unless the system is bled to remove all air pockets, it is possible that negative pressure pulses can occur, rendering the recorded test data useless.

1. Disconnect the pressure relief valve
2. Remove fuel injector from housing
3. Connect fuel line between the low pressure fuel pump and the measuring tube, bypassing the disconnected fuel injector.
4. Connect a fuel line between the measuring tube and fuel tank.
5. Switch on low pressure fuel pump, creating a circuit of fuel flow from the pump to the tank, via the measuring tube.

6. Allow the pump to run for about 2 minutes, to allow all air pockets to be removed from the circuit
7. Reconnect the pressure relief valve and the fuel injector.
8. Ensure that all connections for the fuel lines, fittings and valves are securely fastened.

### 4.2.4 Testing – Start Up

Upon completion of the bleeding of the fuel lines, the test rig must be prepared for testing, as follows:

1. Connect all power leads to their power supplies.
2. Connect the InjectoBot injection controller to the injector.
3. Connect the pressure transducer on the measuring tube to the charge amplifier.
4. Connect the pressure transducer on the common rail to the charge amplifier.
5. Connect the charge amplifier from the strain gauge to channel one of the data logger.
6. Connect the charge amplifier from the measuring tube pressure transducer to channel two of the data logger.
7. Connect the charge amplifier from the common rail pressure transducer to channel three of the data logger.
8. Turn on the laptop and start up the Hard Disk Logger software.
9. Switch on the data logger and connect it to the system.
10. Ensure that the Hard Disk Logger software on the laptop is able to control the data logger.
11. Using the software, set the start and stop triggers to manual and set the sampling rate to 20μs.

### 4.2.5 Testing

Once the procedures described above have been carried out, the rig should be ready to carry out tests. This testing is described as follows:

1. Ensure there is sufficient diesel in the tank.

2. Switch on the following, ensuring, where applicable, that they are zeroed:
    - Strain gauge amplifier:
    - Charge amplifier from measuring tube pressure transducer.
    - Charge amplifier from common rail pressure transducer.
3. Switch on (if not already on) the InjectoBot and set the desired frequency and duration for the test to be done.
4. Switch on the low pressure pump, the rail pressure sensor and the rail pressure relief valve.
5. Wait about one minute for the high pressure pump to be primed from the running of the low pressure pump.
6. Switch on the induction motor that powers the high pressure pump.
7. Adjust the rail pressure to the desired pressure for the test that is to be done.
8. Switch on the InjectoBot (upon doing so, the sound of each injection should be audible).
9. Adjust the relief valve to the required back pressure.
10. On the laptop, begin recording data, allowing for roughly five injections to occur, and then stop the recording.
11. Save the data to a csv file on the hard drive of the laptop.
12. Alter the injection duration and frequency on the InjectoBot as well as the rail pressure for the next test that is to be done.
13. Repeat steps 3-12 for the required tests.
14. Disconnect all power supplies.
15. Disconnect the amplifiers from the sensors and the data logger.
16. Turn off and disconnect the data logger and the laptop.
17. Clean all fuel that has spilled/ leaked duration testing.

# 5 Observations

The observations are divided into three rounds of tests. Although still insightful, test rounds one and two were not successful according to the described method in Section 4.2.1. That is, the number of tests at the prescribed settings for pressure, duration and frequency were not carried out, and injection pulses were not consistently recorded. However, as the tests did provide insight (the injection pulses were recorded and the flow rate calculated and correlations between the parameters could be made) the observations are given below and their results discussed in Appendix 3. The main focus however, is on the complete, third round of testing.

## 5.1 Testing Round 1

Table 3 describes the variables for each of the tests that were carried out. Only test number 4 produced voltage readings correlating to the pulses from the fuel injector. All the other readings showed no discernable patterns and were therefore discarded.

**Table 5-1: Testing Data for Test Round 1**

| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | **Injecto-Bot Frequency (Hz)** | 15 | 15 | 15 | 15 | 10 | 10 | 10 | 1 | 1 | 1 | 1 | 10 |
| **2** | **Injecto-Bot Duration (ms)** | 6.4 | 6.4 | 5.2 | 3.2 | 3.2 | 5.2 | 6.4 | 6.4 | 5.2 | 3.2 | 3.2 | 3.2 |
| **3** | **Rail Pressure (bar)** | 500 | 500 | 500 | 500 | 500 | 500 | 500 | 500 | 500 | 500 | 500 | 500 |
| **4** | **DAC Duration (s)** | 12 | 5.12 | 5.12 | 5.12 | 5.12 | 5.12 | 5.12 | 5.12 | 5.12 | 5.12 | 6 | 6 |
| **5** | **Injector Holes** | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 |

Figure 5-1 and Figure 5-2 display the voltage versus time (sampling interval) recordings for test run 4, clearly showing the correlation of the injections recorded by both the strain gauge and the pressure transducer to each other.

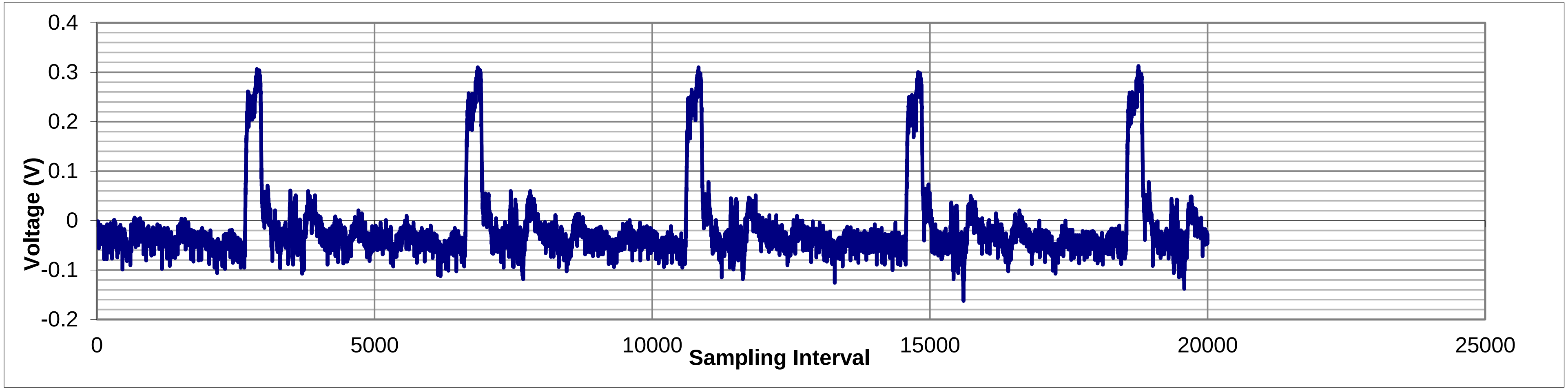


**Figure 5-1: Strain Gauge Voltage for Test Run 4**

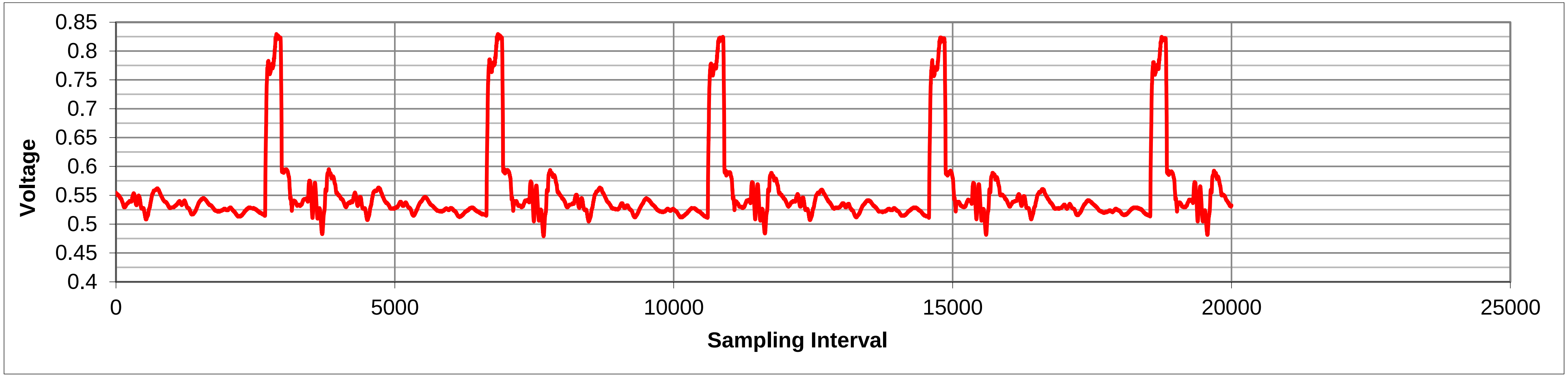


**Figure 5-2: Pressure Transducer Voltage for Test Run 4**

## 5.2 Testing Round 2

At a later stage, subsequent to the repairs and replacements required of the strain gauge and the InjectoBot, an attempt at completing more tests was carried out. The same experimental procedure was employed, with the only difference being that the data was displayed and stored on the handheld data logger itself and there was no need for the use of a laptop computer, as discussed in Section 3.2.3.

The frequency for recording of data points was reduced from 20 kHz in the initial testing to 4.096 kHz. The motivation for this change was that, although the resolution will decrease, and it may not be possible to fully analyse the shape of the injection curve and understand the injection characteristics, it will allow for a larger amount of injections to be recorded (improving the chances of gaining useful readings). It was intended that if the testing was fully successful, another round of tests would be carried out at a frequency closer to 20 kHz.

Once again, the vibration on the test rig was substantial. There was concern that no results would be obtained until the rig was overhauled, so that the majority of the vibration caused during the running of the rig, could be eliminated.

The large amount of vibration in the system was seen as a major concern, and it was decided that during the experimentation, in order to keep the complexity to a minimum, only 1 parameter would be changed for each test run. The reason for this was to allow for complexity in the design of the experiments to be kept to a minimum while still allowing for some insight into how one of the injection parameters affects the injection flow rate. If two factors were made variables, as was done in the initial round of testing, it would be more difficult to determine the role of the vibration in affecting the flow rate, and to differentiate its effect from the effect caused by changing just one parameter with each test run.

It was decided that the variable in the tests was to be the injection frequency, as this allowed for the most visible change in the injection recordings (more injection pulses per unit time), easy to notice on the graphs of the data (this was an iterative process, as described in Section 4.2.1). This was increased with each test run. 6 test runs were carried out. However, there were only three of the runs that recorded data that accurately depicted the injection of the fuel through the injector. The parameters for the testing can be found in Table 5-2 and Table 5-3 below.

**Table 5-2: Variable Parameters for Flow Rate Testing**

| Reading | InjectoBot Frequency (Hz) | InjectoBot Duration (ms) | Voltage (V) | DAC Recording Duration |
|---|---|---|---|---|
| a | 0.3 | 3.2 | 1.4 | 6 |
| b | 0.9 | 3.2 | 1.4 | 7 |
| c | 1.2 | 3.2 | 1.4 | 8 |
| d | 2 | 3.2 | 1.4 | 8 |
| e | 2.8 | 3.2 | 1.4 | 8 |
| f | 3.5 | 3.2 | 1.4 | 8 |

**Table 5-3: Constant Parameters for Flow Rate Testing**

| | |
|---|---|
| **Common Rail Pressure (bar)** | 500 |
| **Injector Type** | Electronic, 6-hole |
| **Fuel Type** | Diesel |
| **Channel 1** | Strain Gauge |
| **Channel 2** | Pressure transducer |
| **Data points for each reading** | 65000 |
| **InjectoBot Duration (ms)** | 3.2 |
| **Voltage (V)** | 1.4 |

For clarification, Table 5-2 lists the readings as a-f, but as only three of the readings were successful (b, c, and e), from this point onwards, the successful readings are referred to as test runs 1(b), 2(c) and 3(e).

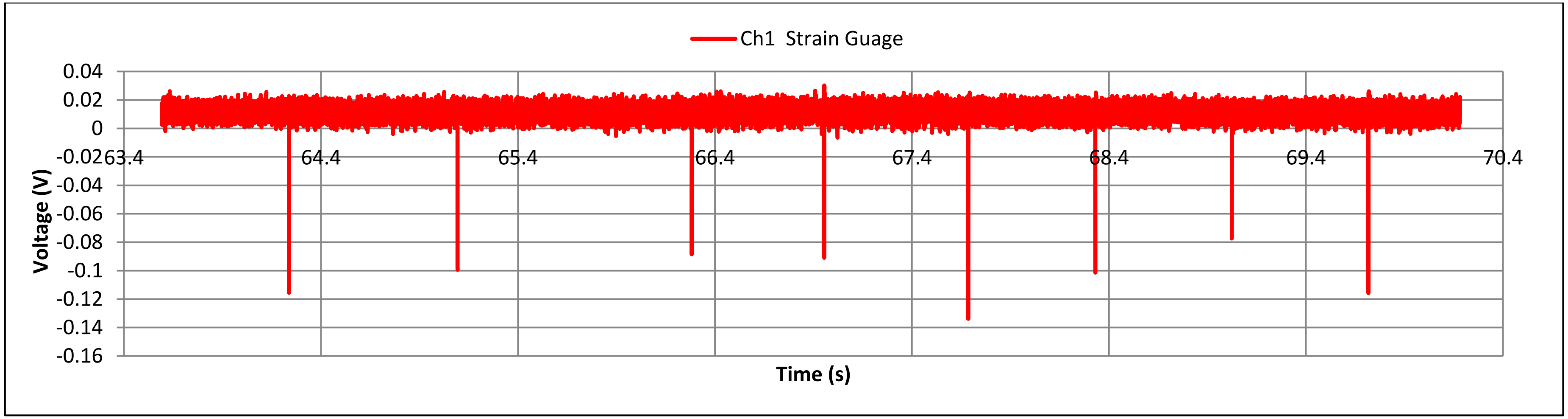


**Figure 5-3: Voltage Variation of Strain Gauge for Test Run 2**

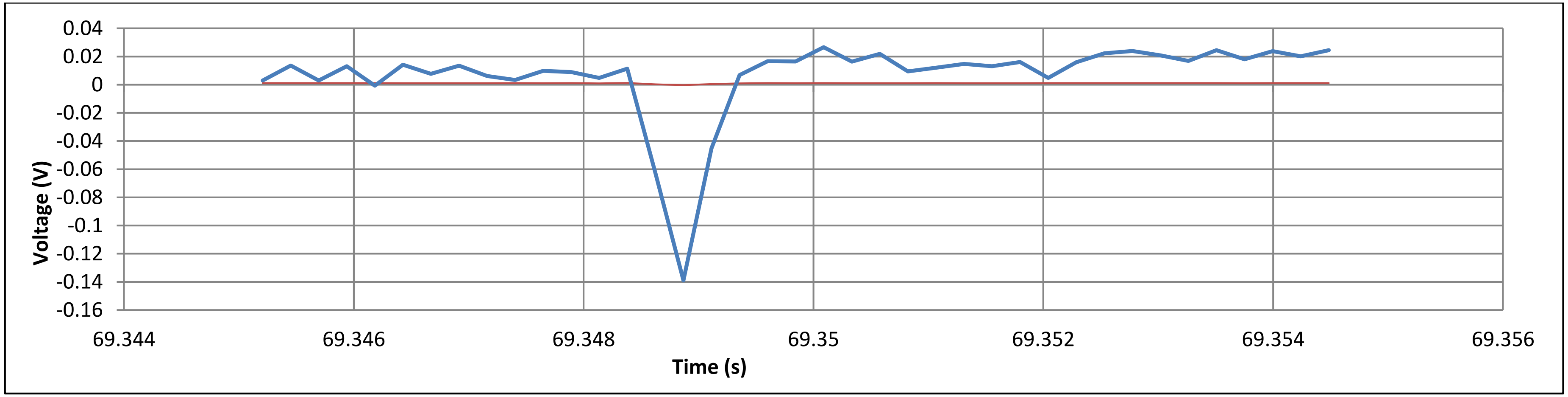


**Figure 5-4: Voltage Variation for a Single Injection Pulse for Test Run 2**

It was seen that initially, the injection pulse was not reflected in the data logger output. After manipulation of various components on the rig while it ran, a signal from the injections was observable. Whenever this was seen, recording of the pulses was carried out. 6 recordings in total were carried out, but for some reason (which was likely due to the noise interference from the vibration of the system), only three of the readings recorded correctly to the data logger. There was also only one test run where both channel 1 and 2 successfully recorded voltages (test run 3). This meant that only the strain gauge readings were recorded to the data logger for test run 1 and 2. Figure 5-3 and Figure 5-4 depict the injection pulses recorded and the isolation of a single injection as well.

## 5.3 Testing Round 3

Due to the small amount of data that was obtained from the first two rounds of testing, a third, more substantial set of tests was required. A final year undergraduate student, Rice [27], was tasked with carrying out these tests. The tests were carried out on the same test rig that the earlier work was done. As before, the results were received from the student as voltage values for both the strain gauge and pressure transducer located on the test rig, and were presented in csv file format.

Data was recorded for various rail pressures, injection durations and frequencies, as described in Table 4-3. The data from this third round of tests was far more comprehensive than those of the first two rounds of tests, and is where the majority of the analysis that is done comes from.

Figures 5-5, 5-6 and 5-7 depict the change in voltage with sampling interval, and therefore with time, for a test run at 300bar rail pressure, with an injection frequency of 0.58Hz and duration of 3.2ms. Although not equal in magnitude, the injection pulse clearly results in an increase in voltage for both the strain gauge and the pressure transducer. For the rail pressure, it is seen that the pressure drops as the injection pulse occurs (Figure 5-7). In Figures 5-6 and 5-7, the first wave can be seen followed by 4 distinct reflected waves, which gradually decrease in magnitude. For the rail pressure, there is a significant dip in voltage, and this slowly climbs, with less variation. Figure 5-8 depicts the change in voltage for the set of tests at each of the rail pressures tested. The higher voltage clearly correlates to a higher rail pressure.

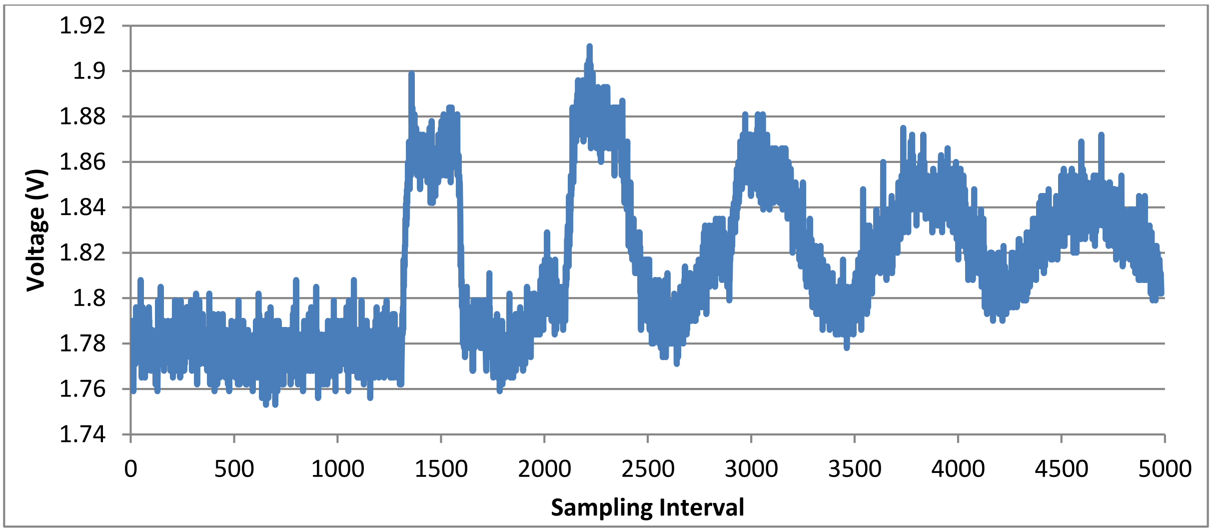


**Figure 5-5: Strain Gauge Voltage Variation**

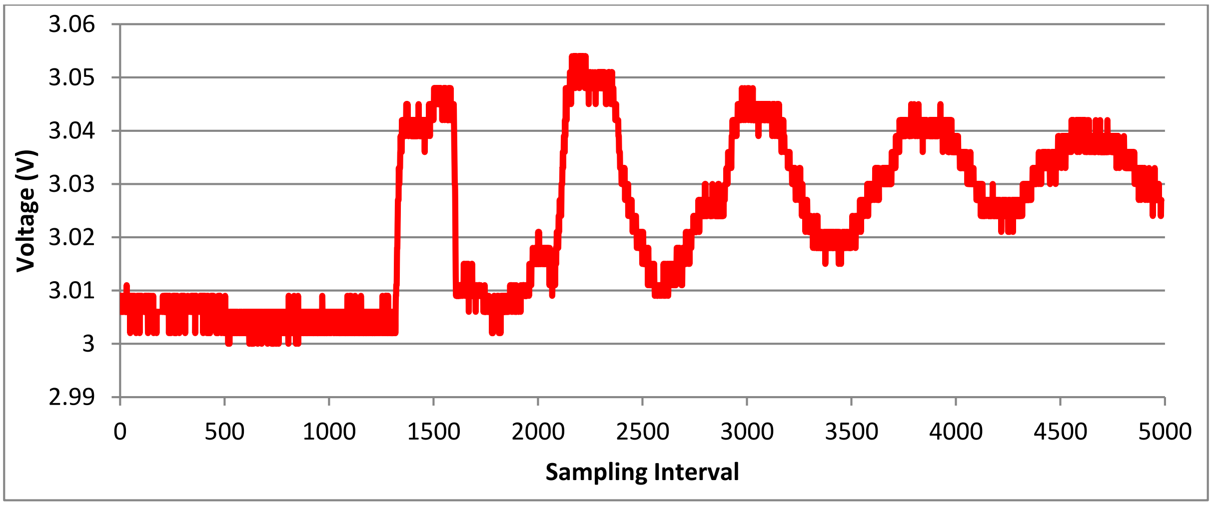


**Figure 5-6: Pressure Transducer Voltage Variation**

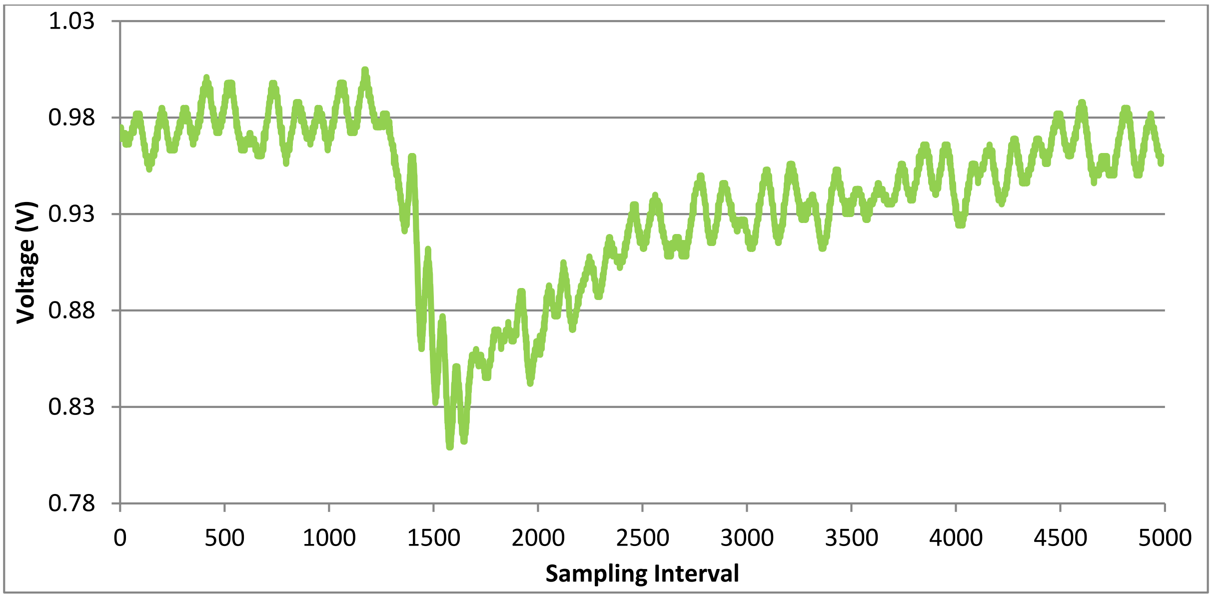


**Figure 5-7: Rail Pressure Voltage Variation at 350 bar**

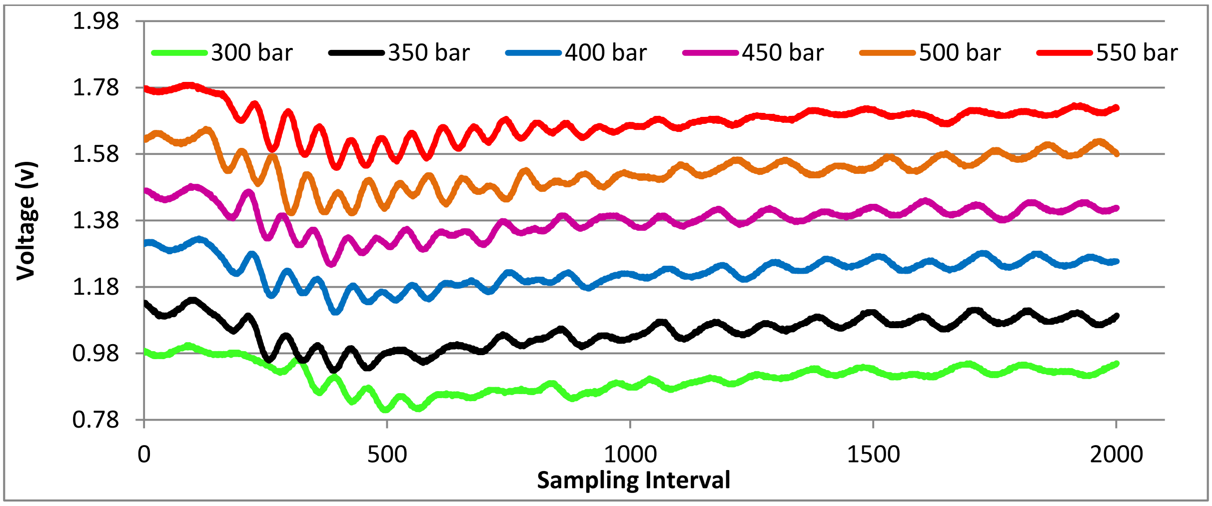


**Figure 5-8: Rail Voltage Variation at all Pressures Tested**

# 6 Data Processing

## 6.1 Flow Rate Calculations

The equations described in section 4.3 are used to derive the pressure and flow rate for each of the injections. A sample calculation for the test run at rail pressure of 300bar, 3.2ms injection duration, and 0.58Hz injection frequency can be found in Appendix 1.

Appendix 1 also contains the excel setup used for the calculation of pressure and flow rate with the pressure transducer and strain gauge for each of the 54 tests. It also shows the pressures and corresponding flow rates calculated from the strain gauge and pressure transducer voltages for tests at the lowest and highest pressures (300bar and 550 bar).

## 6.2 Sensitivity Analysis

In order to better understand the source of the uncertainty within the results of the experimentation, as well as to quantify it, a sensitivity analysis was carried out. Local methods, making use of partial derivatives were employed.

For the sensitivity analysis, three sources of uncertainty were identified:

Voltage reading, ΔV = ±0.0005V, resulting in a pressure reading uncertainties of: $\Delta P_{strain\ gauge}$ = ± 0.1 bar and $\Delta P_{pres\ trans}$ = ± 0.31 bar.

Speed of sound of diesel, $\Delta a$ = ±30m/s.

Diameter of the measuring tube, Δr = ±0.25mm, resulting in an area uncertainty of: ΔA = ±4.713mm$^2$.For each reading, the uncertainty in the flow rate is calculated by combining the partial derivatives [28]:

$$\Delta Q = \left|\frac{\partial Q}{\partial A}\right| \Delta A + \left|\frac{\partial Q}{\partial P}\right| \Delta P + \left|\frac{\partial Q}{\partial a}\right| \Delta a\ ,$$

this can then be expressed in terms of equation [2]: Q = PA/αρ

$$\Delta Q = \left|\frac{P}{a\rho}\right| \Delta A + \left|\frac{A}{a\rho}\right| \Delta P + \left|\frac{PA}{\rho}\right| \frac{1}{\Delta a}$$

The uncertainty in the flow rate from the flow rate for the two sensors is:

- Pressure Transducer: ±0.5 mm$^3$/s
- Strain Gauge: ±1.8 mm$^3$/s

The uncertainty from the calculation of the theoretical flow rate is found to be: ±0.046 mm$^3$/s.

# 7 Results

Comparing the volumetric flow rate calculated for the strain gauge and the pressure transducer, there is a discrepancy in their flow rates. However, the discrepancy is consistent for all 54 of the tests run, indicating that both the strain gauge and pressure transducer are recording accurately and that the gain factors used in the calculation of the flow rates are most likely incorrect, or that the location between the two gives a different strength of injection. However, as both sensors are accurately recording, it means that comparisons at various conditions can be made to gain some insight into the relationship between the rail pressure, frequency and duration of injections. If the discrepancy was different for different tests, this would be a problem, but that was not the case.

Figure 7-1 and Figure 7-2 depict the pressure and flow rate calculated for the test at 350bar, 0.58Hz, 3.2ms. The correlation between the two sensors can clearly be seen, as can the discrepancy in the magnitude of the results. The pressure rise of roughly 150bar for the initial injection recorded by the strain gauge, although higher by about 40bar, is consistent to what previous researchers have found (see Figure 8.2 of Catania et al [24]). The second reflected wave can also be seen in Figure 7-1 and Figure 7-2, although it is not as pronounced and the subsequent reflected waves are not very noticeable. The length is roughly 0.68 seconds, or 1/5$^{th}$ of the injection frequency of 0.58Hz (1.73 seconds).

Because of the large number and variation of settings and values, the results are simplified by only showing the flow rates calculated from the pressure transducer, for Figure 7-3 to Figure 7-10.

**Variation of Frequency**

Figure 7-3 toFigure 7-6 depict the flow rate from the pressure transducer. Each curve shows the effect of changing injection frequency on the flow rate while keeping the rail pressure setting and the injection duration constant.

The injection pulses show similar characteristics for the varying frequency. At the lower rail pressure, 300bar, the highest magnitude for flow rate is recorded by the shortest injection frequency – 0.58Hz. This is seen in both Figure 7-3 and Figure 7-4. However, in Figure 7-5 to Figure 7-6, the higher frequency produces very slightly higher flow rates (less than 0.5mm$^3$/s).

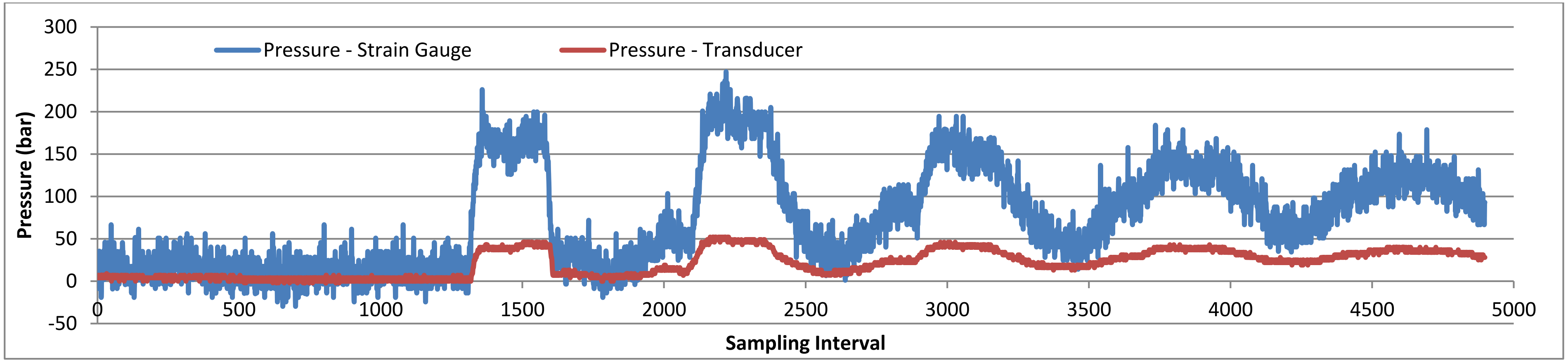


**Figure 7-1: Plot of Pressure at 350bar, 0.58Hz, 3.2ms**

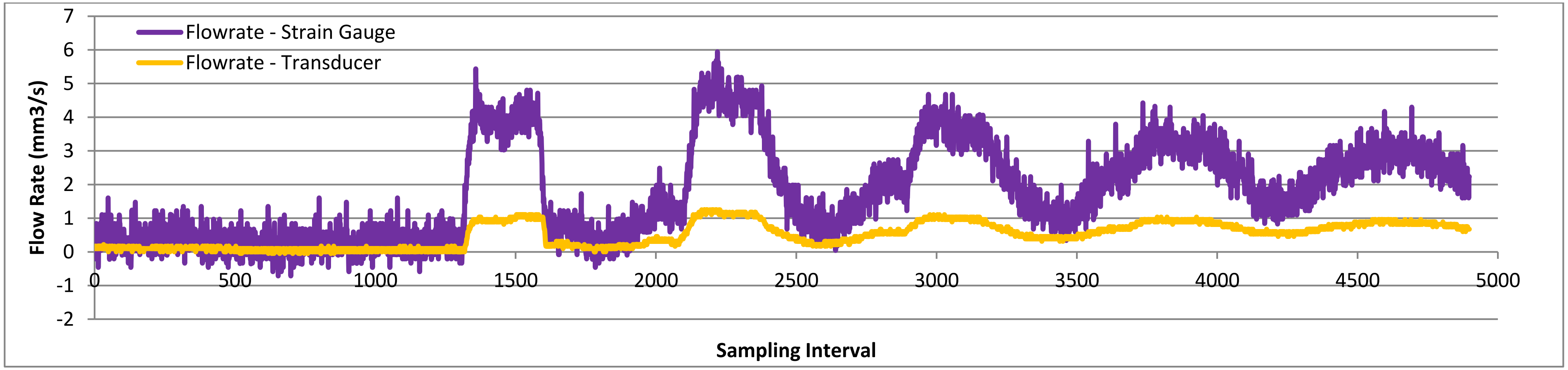


**Figure 7-2: Plot of Flow Rates for 350bar, 0.58Hz, 3.2ms**

There is a correlation between the injection frequency and the duration of the injection pulse (which is seen as the number of sampling intervals between the rise and fall of the curve depicting the injection pulse). For example, in Figure 7-6, the highest injection frequency creates the shortest injection pulse and similarly the lowest injection frequency, 0.58Hz creates the longest injection pulse.

When studying the injection pulses at various injection frequencies, it is also apparent that the curves correlate closest at 300 bar (Figure 7-3), and least at 550 bar (Figure 7-6).

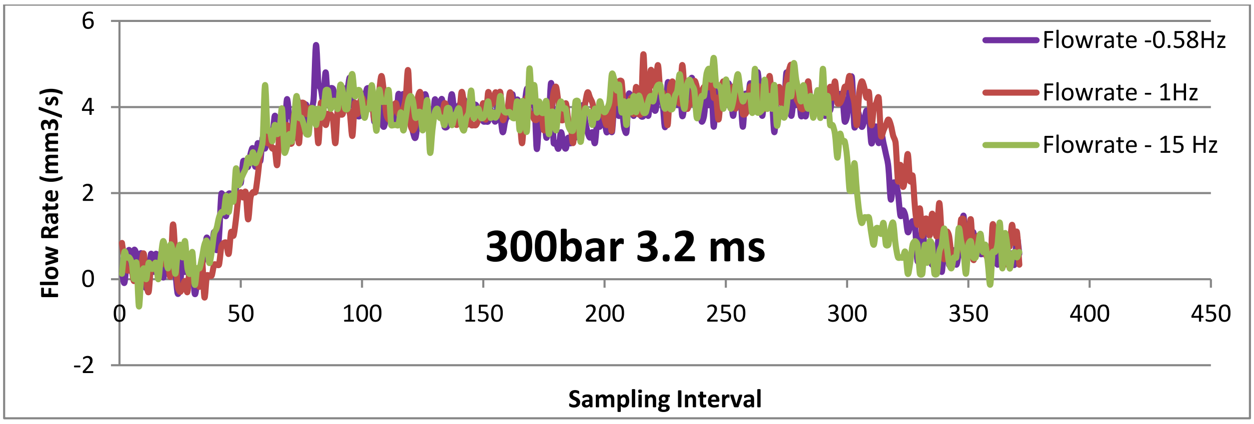


**Figure 7-3: Variation of Frequency at 300 bar, 3.2ms**

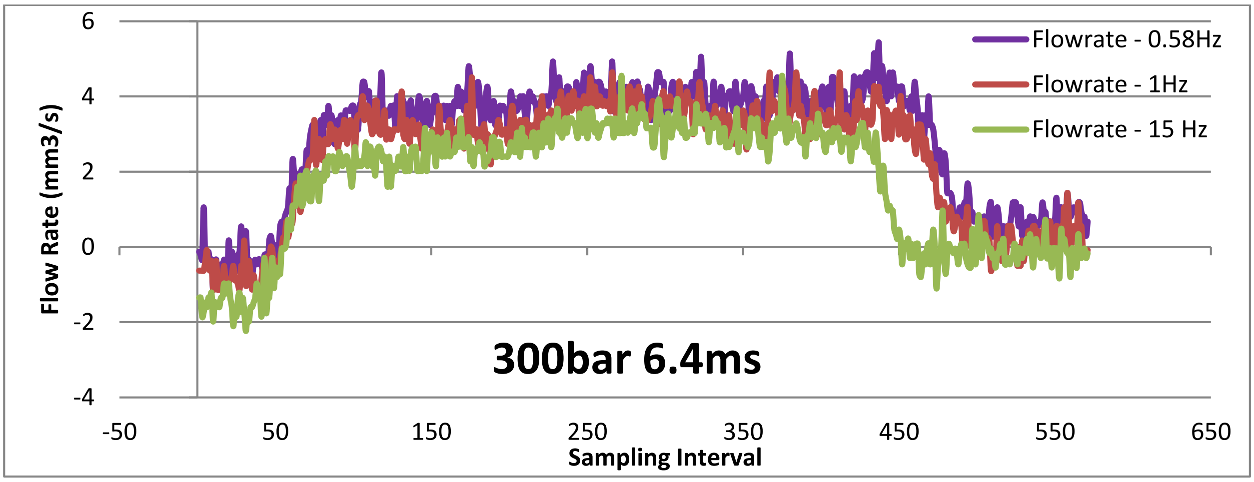


**Figure 7-4: Variation of Frequency at 300 bar, 6.4ms**

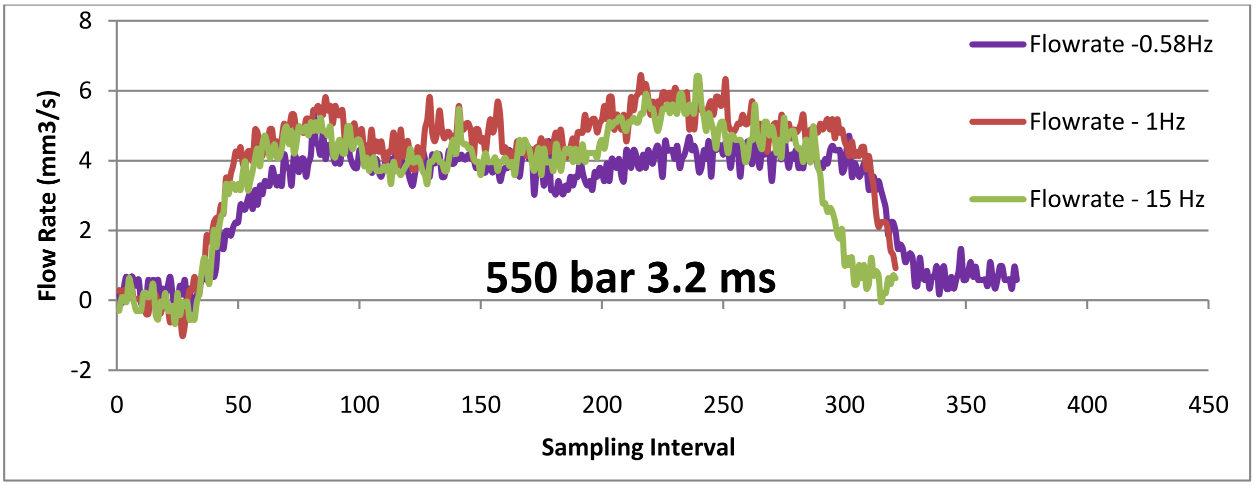


**Figure 7-5: Variation of Frequency at 550 bar, 3.2ms**

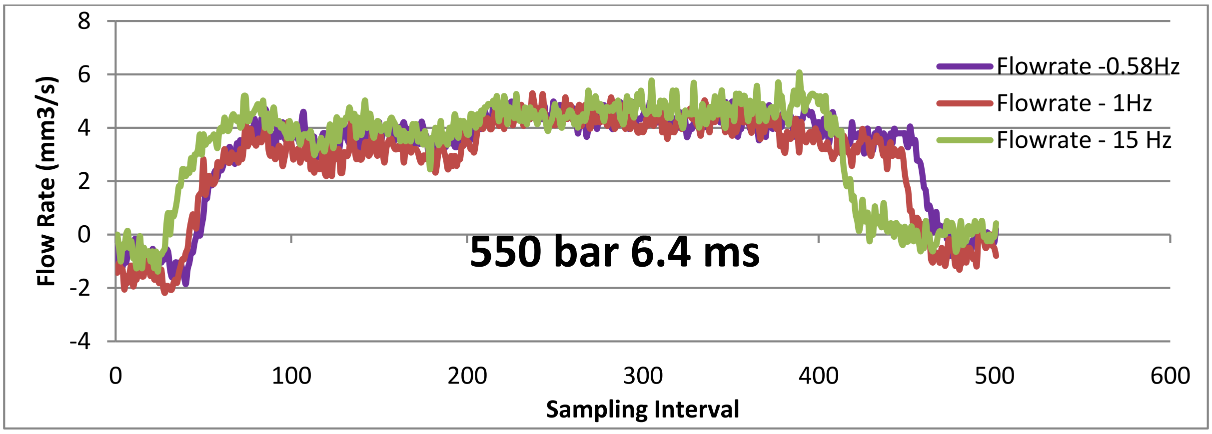


**Figure 7-6: Variation of Frequency at 550bar, 4.6ms**

### Variation of Injection Duration

The next four curves, shown in Figure 7-7 toFigure 7-10 depict the effect on flow rate of changing the injection duration, while keeping the rail pressure setting and the injection frequency constant (for each Figure). Studying the curves, it is clear that the greater the injection duration, the greater the size of the injection pulse. This is intuitive and expected.

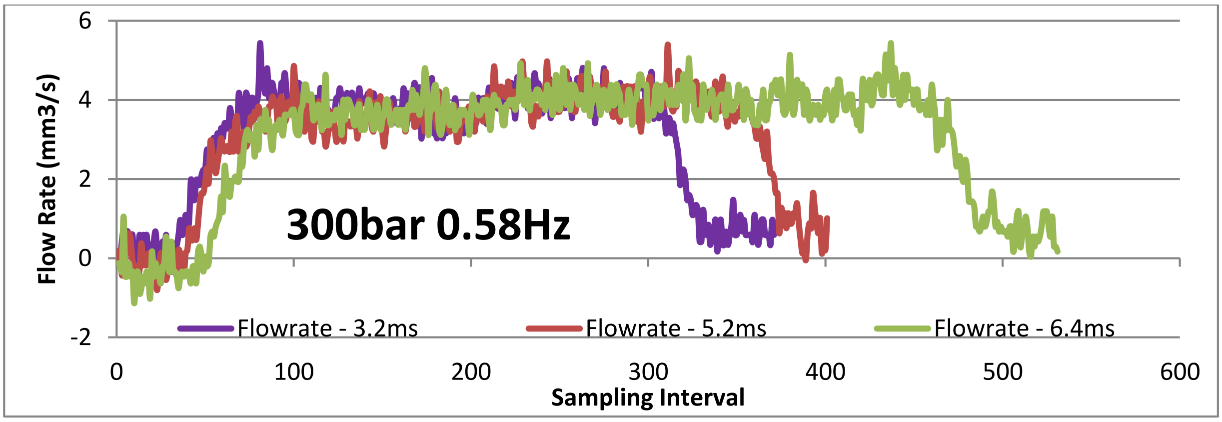


**Figure 7-7: Variation of Injection Duration at 300 bar, 0.58Hz**

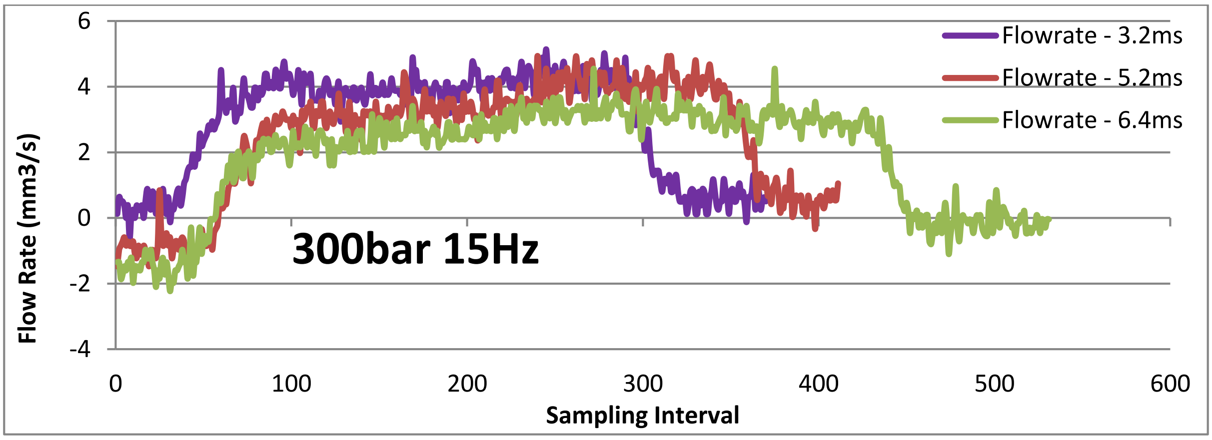


**Figure 7-8: Variation of Injection Duration at 300 bar, 15Hz**

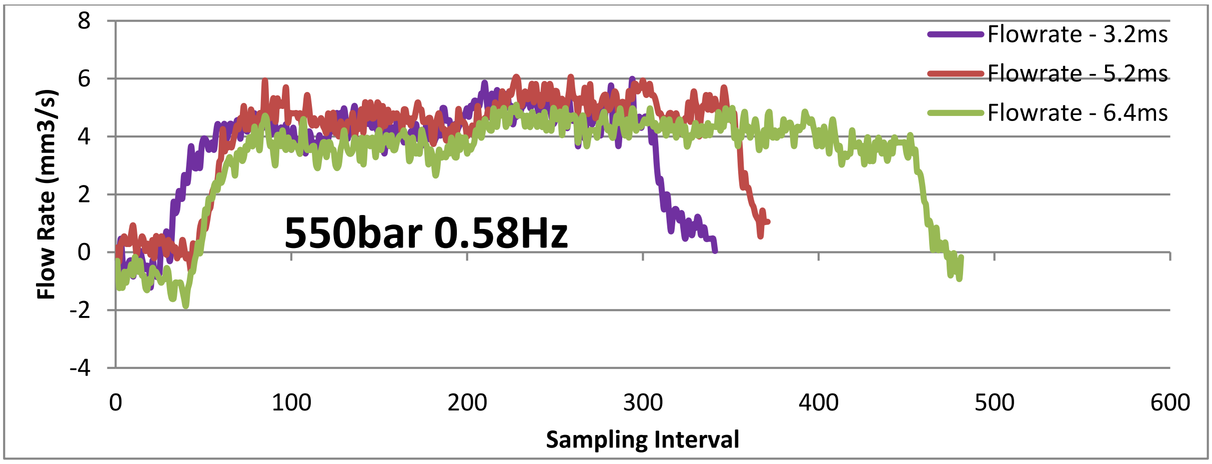


**Figure 7-9: Variation of Injection Duration at 550bar, 0.58Hz**

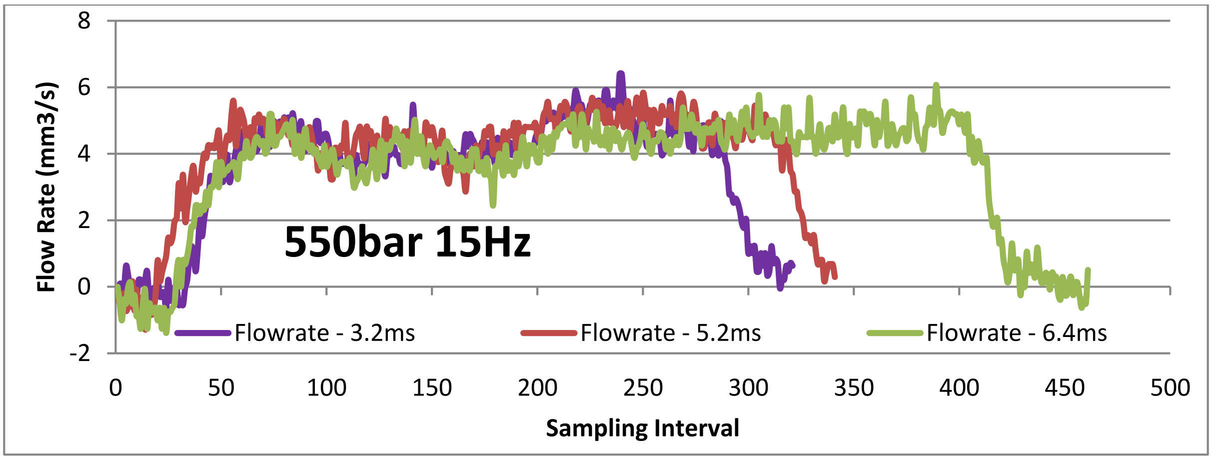


**Figure 7-10: Variation of Injection Duration at 550bar, 15Hz**

As with the injection pulses in Section 7.2.1, it is seen that the closest correlation for varying injection duration occurs at the lowest rail pressure of 300bar and there is most variation at the highest pressure of 550bar rail pressure (in Figure 7-7, the flow rates are almost super-imposed on each other, while the three curves have differing flow rates in Figure 7-10). This correlation however is only in terms of the flow rate during the injection, and not the duration of the injection, which of course, is what is being varied.

**Variation of Rail Pressure**

The rail pressure is determined at various intervals, from 300bar to 550 bar. Although there is not a large change in the shape of the curves for each pressure, it can be seen in Figure 7-11 that the injection drop and subsequent gradual recovery in pressure is very slightly increased at higher pressures.

It is also seen that the lower rail pressure is associated with lower flow rates with Figure 7-7 to Figure 7-8 having peak flow rate values around 3.5 $mm^3/s$ and Figure 7-9 and Figure 7-10 having values around 5.5$mm^3/s$.

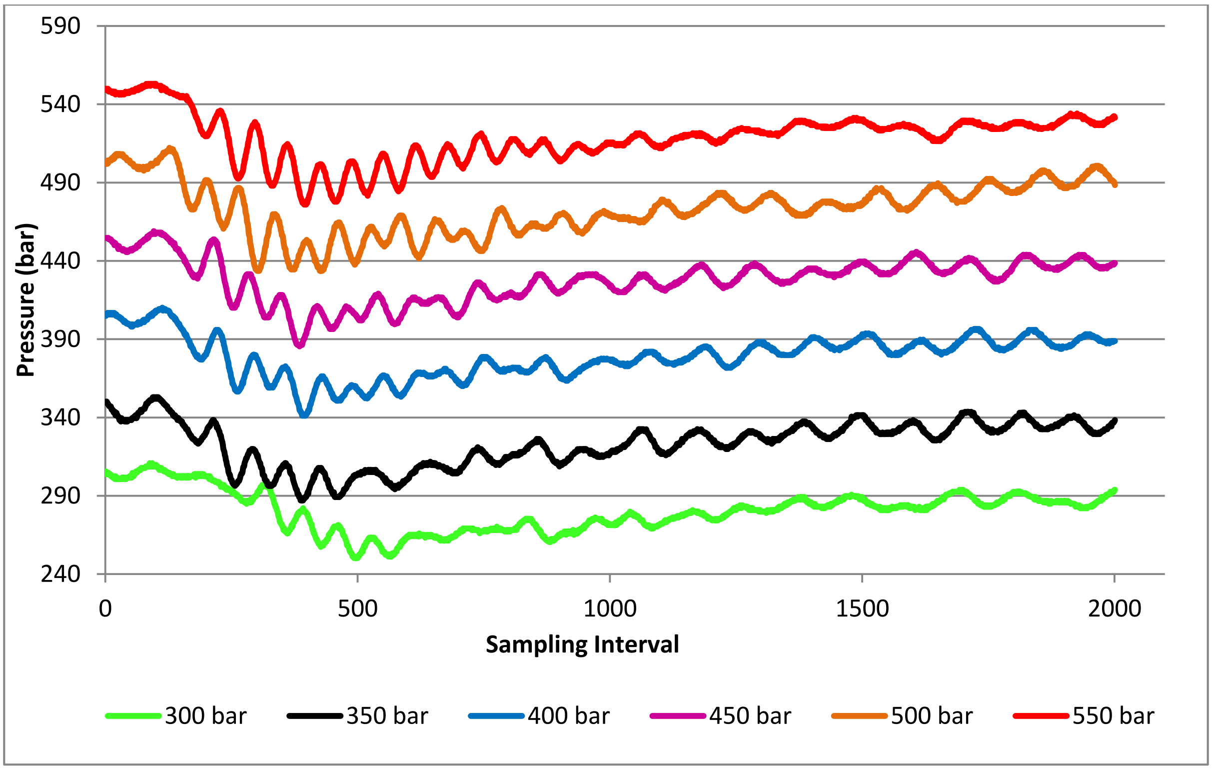


**Figure 7-11: Variation of Rail Pressure at Various Pressure Differentials**

# 8 Discussion

The rig was modified and prepared as required. The fuel tank was fitted and the strain gauge and injection controller repaired, allowing testing of the diesel fuel under various conditions to take place. Problems were encountered during the testing and it had to be divided into three rounds, making the process an iterative one, continuing thrice until the results were achieved in the correct manner. The data from the tests was successfully recorded and processed and various patterns emerged in the results.

Although insightful, the data from the initial two rounds of testing was not as significant as the data from the third round of testing, conducted by Rice [27]. This is because of the low number of tests in the first two rounds as explained in Section 5. The results and subsequent insights gained from these two rounds are discussed in Appendix 3.

## 8.1 Injection Pulse Description

Figure 7-1 and Figure 7-2 depict the flow rate and pressure for a set of injections, and are placed above each other to highlight the close correlation between the pressure and flow rate as well as between the pressure transducer and the strain gauge readings. In Figure 7-1, there is more fluctuation in the readings for the strain gauge, which may have to do with the level of vibration being different on different sections of the rig. In addition, the strain gauge is more sensitive to vibration that the pressure transducer, both of which are taken into account in Section 6.2. The correlation between the recordings of the injection pulses by the two sensors seen in Figure 7-1 carries through to all 54 of the tests that were recorded. The correlation shows the clear initial injection, followed by various reflected pulses which diminish in magnitude with time. This makes sense as the measuring tube assists in absorbing the shock waves from the pulses.

Figure 7-3 to Figure 7-10 each depict the flow rates for individual injection pulses under various conditions. It can be seen that there is no significant difference in the shape of the injection pulse, regardless of the injection duration, frequency or rail pressure. They all are characterised by a steep rise in flow rate, signalling the start of the injection, followed by a relatively constant flow rate, and then a steep drop in flow rate signalling the end of the injection. The consistent shape indicates that none of the three parameters being investigated have much effect on the nature of the injection pulse.

During the middle of the injection, the curves are not smooth and the readings fluctuate by ±1mm$^3$/s. This can be attributed to two phenomena, the first one being disturbances in the system while the injection is taking place. The greatest source of these disturbances can be attributed to the vibration of the induction motor on the test stand. It must be noted however, that this disturbance is greatly improved (reduced) from the initial testing because of steps taken to reduce vibration, described in Section 3.2.3. Although the disturbances have a very slight effect on the results, as is discussed, the method, results, and insight are still substantially better than the other methods investigated in Sections 2.2 and 3.1 .

The second phenomenon is the slight drop in pressure in the common rail attributed to the flow of fuel out of the injector. This is what was also found by Catania et al [24].

## 8.2 Effect of Injection Frequency

The flow rates were calculated, and curves were generated with the pressure and the injection duration remaining unchanged, so that the results at various injection frequencies could be compared.

It was found that the injection duration, although kept constant by the electronic injector controller, was related to the injection frequency; the higher the frequency, the shorter the injection duration. In all the Figures 7-3 to 7-5, the green curve, 15Hz, traces the shortest injection duration. The effect is however not very large, and it would require an extremely high injection frequency to significantly lower the duration. This phenomenon can be attributed to the lowering of the rail pressure that occurs when the injection frequency is high. That is, high frequency injection reduces the rate at which the rail pressure can be recharged. This common rail pressure change is the same phenomenon described in Section 8.1.

When studying the magnitude of the flow rates, there is negligible change with changing frequency. It can therefore be concluded that the flow rate is not affected by changes in the injection frequency. It must be noted that the actual flow per unit time will be unchanged, but that, with a higher frequency of injections, more fuel will obviously be injected.

When studied in conjunction with the work done by Khan [21], (discussed at the end of Section 3.1.1) it is found that the outcome is the same – the frequency of injection does not significantly affect the flow rate.

This correlation does not carry over to the work done by Catania et al [24] (also discussed in section 3.1.1), although this is because the frequencies are high enough for fusion to occur, which changes the nature of the injection and therefore also the flow rate. Although the effects of fusion are to be considered when investigating the frequency of fuel injections, for the testing done in this research, the frequencies were too low for fusion to occur and therefore it can be considered unimportant that the correlation did not carry over.

## 8.3 Effect of Injection Duration

The flow rates were calculated, and curves were generated with the pressure and the injection frequency remaining unchanged, so that the results at various injection durations could be compared.

The effect of changing the injection duration on the injector controller is clearly visible as the injections become longer with increasing duration. This is expected, and is useful as a verifier that the injection controller is working as expected.

It can be seen by studying Figures 7-6 to 7-8, that changes in the injection duration do not significantly affect the flow rate of the fuel. However, there is a very slight reduction in flow rate at the longest injection duration, which may suggest that the long injection durations reduce the pressure in the common rail, thereby reducing the flow rate. This would however require testing at extended injection durations for verification, and from the tests conducted under the general injection conditions of most common rail engines, it can be concluded that the flow rate is independent of the injection duration.

This is in significant contrast to the findings of Khan [21], where the relationship between the injection duration and the flow rate was a linear one. It is unclear why this is the case. The result is therefore not reliable as the literature reviewed provides different findings (such as Khan's [21]).

## 8.4 Effect of Rail Pressure

The flow rates were calculated, and curves were generated with the pressure and the injection frequency remaining unchanged, so that the results at various injection durations could be compared.

Studying Figure 7-11, it can be seen that a higher rail pressure brings about two slight changes in the nature of the rail pressure change over the duration of the injection. That is, the pressure drop is greater, and the recovery of the rail pressure back to its pre-injection value occurs slightly faster. This seems intuitive as a higher pressure in the common rail would cause a higher recharge rate.

Once again looking at Figures 7-3 to 7-10, but comparing the figures with different rail pressures, it is noticeable that, of the three variables tested, only the rail pressure has any effect on the flow rate of the fuel through the injector. The higher the common rail pressure, the higher the flow rate. Both Watkins [22] and Khan [21] determined the same relationship between pressure and flow rate.

This is insightful as it means that, when determining the most suitable combination of injection duration, frequency and rail pressure for optimum combustion of fuel, only one parameter has to be monitored for fuel consumption and that is the rail pressure.

# 9 Conclusions

Upon completion of the research on the fuel indicator test rig, it can be concluded that:

- The objectives of the research were met:
    - The rig was prepared and modified for experimentation
    - Testing with diesel fuel was carried out
    - The relationships between the flow rate of the fuel and the injection frequency, duration, and rail pressure is now better understood.
- There was no correlation between the injection frequency and the injection duration, except that at very high frequencies there seem to be slight reductions in the injection duration. This would require further verification however.
- The testing found no correlation between injection frequency and fuel flow rate, however, this is not consistent with the work of previous researchers, prompting the requirement of further testing.
- The testing found no correlation between injection duration and fuel flow rate, however, this is not consistent with the work of previous researchers.
- The higher the rail pressure, the greater its drop after an injection pulse and the greater its recovery rate to pre-injection pressure.
- As the pressure in the common rail increases, so does the flow rate of the fuel through the injector.

The points mentioned above show that the research did contribute to the body of knowledge regarding the relationship between the three parameters measured (injection pressure, duration and frequency) and therefore meets the original purpose of this research report.

# 10 Recommendations

- Further testing should be carried out at as high frequencies as is possible with the test rig in order to confirm that the injection duration slightly decreases the injection duration. This would require modification of the InjectoBot electronic injection controller.
- Further testing should be done to determine the discrepancy between this work and work by others on the relationship between frequency and fuel flow rate, under different conditions such as different rail pressures.
- The rig should be modified in order for testing with DME to be carried out. The DME testing should compare the same three parameters to confirm that the relationships are dependent on the injector and not the nature of the fuel being used.

In addition to the above recommendations, the main aim described in the introductory chapters should always be kept in mind. That is, to gain a deeper understanding of the relationship between the factors affecting common rail engine performance and efficiency, in order for both of these to be improved, while also improving emissions. This research report's significance is that it has, if only in a small part, contributed to this end goal.

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# Appendix 1

## A1.1 Sample Calculations

The sample calculation is for a test run at rail pressure of 300bar, 3.2ms injection duration, and 0.58Hz injection frequency.

The values for the constants in equations (1) – (4) are as follows:

$k_{1s} = 1776$ kPa/cm$^2$

$k_{1p} = 50$ bar/V

$\varsigma = 0.987$

The cross-sectional area of the measuring tube and the density of the diesel fuel for the test conditions are calculated, to provide the following values:

A = 28.27mm;

$\rho = 0.00084$ g/mm$^3$;

$\alpha = 1\,400\,000$ mm/s

**Strain Gauge**

The average voltage for the injection peak is 0.084V.

Using equation (1), the pressure is calculated as:

$P = \zeta.k_{1s}.V$

$= 0.987 \times 1776 \times 0.093$

$= 163.02$ bar

Then, from equation (2) the flow rate calculated as:

$Q = PA/\alpha\rho$

$= (163.02 \times 28.27)/(1\,400\,000 \times 0.00084)$

= **3.918 mm$^3$/s**

**Pressure Transducer**

The average voltage for the injection peak is 0.04V.

Using equation (1), the pressure is calculated as:

$P = \zeta . k_{1p} . V$

$= 0.987 \times 1000 \times 0.04$

$= 39.48$ bar

Again, from equation (2) the flow rate is calculated as:

$Q = PA/\alpha\rho$

$= (39.48 \times 28.27)/(1\ 400\ 000 \times 0.00084)$

= **<u>0.949 mm$^3$/s</u>**

**Rail Pressure**

The rail pressure was calculated by simply multiplying the voltage readings by a gain factor of 309.3 bar/V. Therefore, for the same injection test as in Sections 7.1.2 and 7.1.3, with a voltage for the rail pressure sensor of 0.495V, the rail pressure:

$P_r = 309.3 \times 0.495$

= **<u>153.10 bar</u>**

**Theoretical Flow Rate**

Making use of equation (3) and (4), the theoretical flow rate is calculated. Additional information:

- 6 hole injector.
- $C_d$, the co-efficient of discharge is 0.6
- The area A = 0.4562 mm$^2$
- Back Pressure, $P_b$ = 57 bar

This provides a Pressure Differential of 213 bar, and a flow rate of

**<u>Q = 32mm$^3$/s</u>**

## A1.2 Data Processing

Below are the samples of the calculation framework in Figure A1 and calculated values in Figure A1.

| | CH1 Strn Gauge | | CH2 Pressure Transducer | | Flow Rate Calculations | Values |
|---|---|---|---|---|---|---|
| | Pressure [bar] | Flowrate [mm3/s] | Pressure [bar] | Flowrate [mm3/s] | | |
| 1 | 24.540768 | 0.58993836 | 4 | 0.096156463 | P [bar]= Pressure measured by the strain gauge or pressure transducer | Cols B & D |
| 2 | 1.752912 | 0.042138454 | 4 | 0.096156463 | k1s [kp/cm2] = Strain gauge amplifier gain. | 1776 |
| 3 | -8.76456 | -0.210692271 | 7 | 0.16827381 | k1p [bar/V] = Charge amplifier gain. | ***1000*** |
| 4 | 1.752912 | 0.042138454 | 7 | 0.16827381 | ς = Conversion factor from kp/cm2 to bar | 0.987 |
| 5 | 14.023296 | 0.337107634 | 4 | 0.096156463 | V [V] = Voltage of either the strain gauge or the pressure transducer | |
| 6 | 35.05824 | 0.842769086 | 4 | 0.096156463 | Q [mm3/ms] = Volumetric flow rate of fuel | Cols C & E |
| 7 | 28.046592 | 0.674215269 | 4 | 0.096156463 | A [mm2] = Flow area | 28.27 |
| 8 | 24.540768 | 0.58993836 | 4 | 0.096156463 | a [mm/s] = Speed of sound in diesel | 1400000 |
| 9 | -3.505824 | -0.084276909 | 4 | 0.096156463 | ρ [g/mm3] = Density of diesel | 0.00084 |
| 10 | 7.011648 | 0.168553817 | 4 | 0.096156463 | k - unit conversion factor (putting as 1 for now) | 1 |
| 11 | 1.752912 | 0.042138454 | 7 | 0.16827381 | *P = z ks V* | |
| 12 | 17.52912 | 0.421384543 | 4 | 0.096156463 | *P = z kp V* | |
| 13 | -19.282032 | -0.463522997 | 7 | 0.16827381 | *Q = P A / a p* | |
| 14 | 1.752912 | 0.042138454 | 7 | 0.16827381 | *Q = N Cd A sqrt(2P/p)* | |
| 15 | 7.011648 | 0.168553817 | 7 | 0.16827381 | | |
| 16 | 17.52912 | 0.421384543 | 4 | 0.096156463 | *N = Number of injector holes* | |
| 17 | 28.046592 | 0.674215269 | 4 | 0.096156463 | *Cd= Discharge Coefficient* | |
| 18 | 7.011648 | 0.168553817 | 7 | 0.16827381 | *A= Area of the injector orifice [mm2]* | |
| 19 | 17.52912 | 0.421384543 | 7 | 0.16827381 | *P= Pressure Difference [Pa]* | |
| 20 | 28.046592 | 0.674215269 | 7 | 0.16827381 | *Pb= Back Pressure [Pa]* | |
| 21 | 28.046592 | 0.674215269 | 7 | 0.16827381 | *Pr= Rail Pressure [Pa]* | |
| 22 | 35.05824 | 0.842769086 | 7 | 0.16827381 | *ρ= Density of diesel [kg/m3]* | |

**Figure A-1: Pressure and Flow Rate Calculation Setup**

**Table A-1: Calculated Pressures and Flow Rates for 300 bar and 550 bar Tests**

| ***300bar*** | | | ***Max P Str G(bar)*** | ***Max P Press Trans(bar)*** | ***Max Q Str G ($mm^3/s$)*** | ***Max Q Press Trans(mm3/s)*** |
|---|---|---|---|---|---|---|
| | ***3.2ms*** | ***0.58 Hz*** | 178.00 | 38.00 | 4.00 | 0.96 |
| | | ***1 Hz*** | 180.00 | 43.37 | 4.00 | 0.96 |
| | | ***15 Hz*** | 181.00 | 43.61 | 4.12 | 0.99 |
| | ***5.2ms*** | ***0.58 Hz*** | 159.00 | 38.31 | 3.58 | 0.86 |
| | | ***1 Hz*** | 133.00 | 32.05 | 3.20 | 0.77 |
| | | ***15 Hz*** | 147.00 | 35.42 | 3.53 | 0.85 |
| | ***6.4ms*** | ***0.58 Hz*** | 161.00 | 38.80 | 4.25 | 1.02 |
| | | ***1 Hz*** | 162.00 | 39.04 | 3.87 | 0.93 |
| | | ***15 Hz*** | 153.00 | 36.87 | 3.53 | 0.85 |
| ***550bar*** | ***3.2ms*** | ***0.58 Hz*** | 206.00 | 49.64 | 4.90 | 1.18 |
| | | ***1 Hz*** | 220.00 | 53.01 | 5.30 | 1.28 |
| | | ***15 Hz*** | 205.00 | 49.40 | 4.62 | 1.11 |
| | ***5.2ms*** | ***0.58 Hz*** | 210.00 | 50.60 | 5.50 | 1.33 |
| | | ***1 Hz*** | 203.00 | 48.92 | 5.10 | 1.23 |
| | | ***15 Hz*** | 190.00 | 45.78 | 4.90 | 1.18 |
| | ***6.4ms*** | ***0.58 Hz*** | 191.00 | 46.02 | 4.80 | 1.16 |
| | | ***1 Hz*** | 185.00 | 44.58 | 4.60 | 1.11 |
| | | ***15 Hz*** | 220.00 | 53.01 | 5.20 | 1.25 |

# Appendix 2 – Rig Repairs and Modifications

The following section describes the work done on the rig in order for it to be suitable to carry out the tests that were required.

### Fuel Tank

The fuel was being stored in a plastic container, but this was being decomposed by the diesel fuel. Therefore a steel container was required, to be used as the diesel sump. A design was developed, along with engineering construction drawings, and the fuel container was fabricated. The most important facets of the tank were the connection where fuel would exit and flow to the pump, and the opening in the top of the tank where fuel would be returned after passing through the test rig.

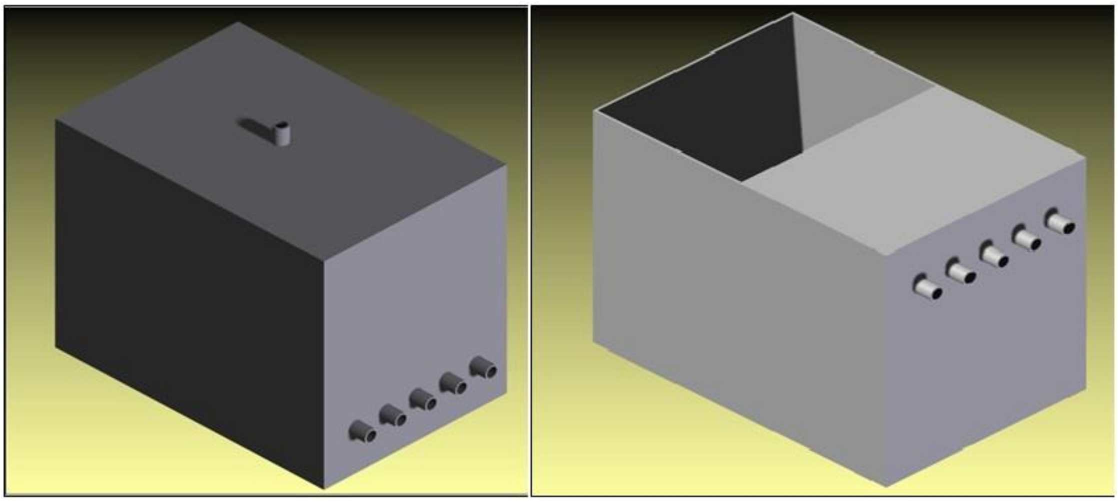

**Figure A-2: Fuel Sump with Connection Ports**

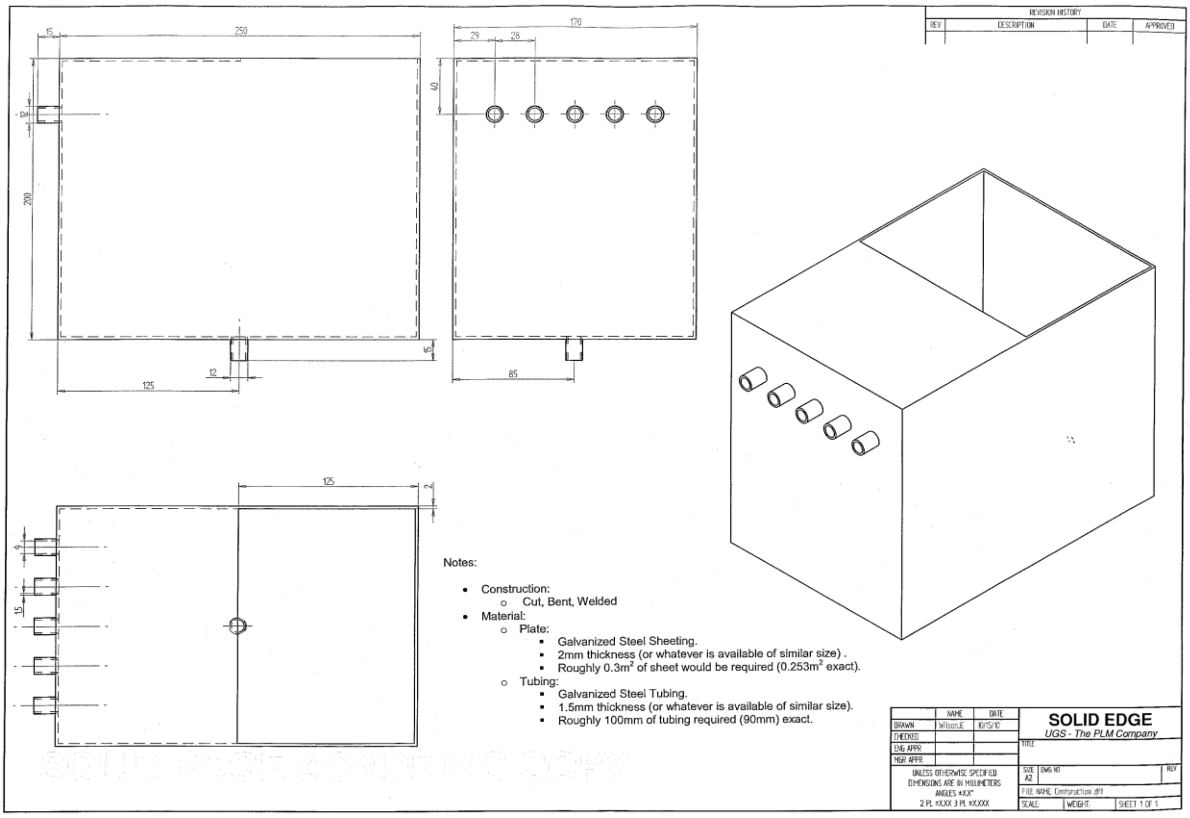


**Figure A-3: Construction Drawing of Fuel Sump**

### Injector Controller Repair

The electronic injector controller InjectoBot, designed, constructed and tested by Mclean [26], was used not only in the fuel rate indicator test rig, but also for various other test rigs where injector control was required (such as the injection spray pattern analysis rig).

At the time when this work began, the InjectoBot was not working. It was not clear why it did not work or when it was that it stopped and so an overall troubleshooting approach was taken. The design of the circuit was reviewed, in order to gain an understanding of how the system worked and exactly where each component linked to the next, as well as how it was configured. Checks that the connections were intact were done. As the components were relatively low cost, it was decided that all three of the major components were to be replaced: the MOSFET chip, the 555 timer (which seemed most likely to have been overloaded by an incorrect connection to the power source) and the heat sink that was placed next to the MOSFET to dissipate the heat that can build up during operation. They can all be seen on the photograph of the bread board in Figure 6.

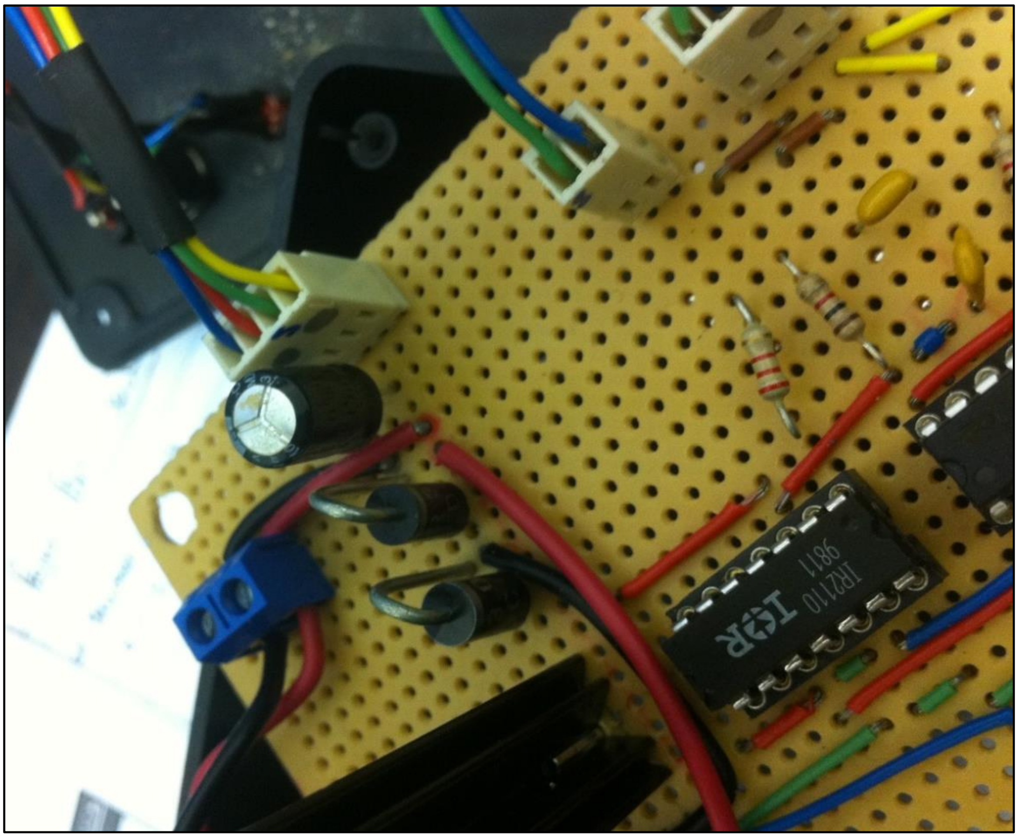


**Figure A-4: Breadboard of InjectoBot showing MOSFET and other Components**

### Strain Gauge Repair

Subsequent to the first set of tests being run, it was found that the strain gauge was not working. During the research and testing, the rig had been used by other researchers, and the strain gauge had been damaged (it was later found to have been dislodged from the tube wall on which it had initially been secured).

As the researcher had little experience with strain gauges, it was sent for repair to Mr Louis Eder, a specialist in strain gauge manufacturing, measurement and fabrication, and the original supplier of the strain gauge. The internal injector tube where the strain gauge was supposed to be attached along with the strain gauge and the bespoke amplifier that accompanied it were returned and he carried out repairs on them. Because of his workload, the repairs took a considerable period of time, and no testing was possible on the rig for about 6 months.

Upon receipt of the repaired strain gauge, it was set back in place and tested, and found to be working as expected.

Other righ changes were:

- The rig overhaul

- The change from sata storage on a laptop to a handheld data logger
- Recording frequency changing from 20kHz to 4.096kHz

# Appendix 3

The following is a discussion on the insights gained from the initial two rounds of testing.

**Testing Round 1**

The equation P=kV was used to determine the pressure. A strain gauge amplifier gain of k=1776 kPa/cm$^2$ was used for the pressure calculation in the strain gauge, while a value of k = 50bar/V was used for the pressure transducer. Equation **(2)** was then used to determine the flow rate of the diesel at the exit of the fuel injector.

Upon inspection of the curves for the voltage readings for each of the 11 test runs, it is seen that there are no clear trends, except in test run number 4 (shown in Figure 5-1 and Figure 5-2), which clearly display recorded pulses from both the strain gauge and the pressure transducer. It is most likely that the amount of noise in the system (cause by the vibration of many of the components on the test bench) rendered the injection vibrations undistinguishable from the noise, and that for test number 4, the tester held onto the measuring tube, damping out a substantial amount of the vibration, allowing a clear set of results to be recorded for this run. Although the tests would have to be repeated for validation, test run number 4 is still interpreted below. The voltage peaks are easily identifiable for both the signals (strain gauge and pressure transducer).

Taking the peak voltage for each injection pulse, the average voltage for both the pressure transducer and the strain gauge were calculated as:

- Average voltage from strain gauge: **0.304V**
- Average voltage from the pressure transducer: **0.827V**

These voltages were used determine the flow rates, as described above, using equations (1)-(4). Table B.1 shows the calculated flow rates for the pressure transducer and the strain gauge, and compares them to the theoretically calculated flow rate.

**Table A-2: Comparison of Flow Rates - Theoretical and Measured**

| Strain Gauge | | | Pressure Transducer | | | Theoretical | | |
|---|---|---|---|---|---|---|---|---|
| P | 5297067.073 | Pa | P | 4134134.615 | bar | N | 4 | / |
| k1s | 177.6 | (kp/cm2)/V | k2s | 50 | bar/V | Cd | 0.6 | |
| ς | 0.980065 | | | | | d | 0.000241 | m |
| V | 0.304325 | V | V | 0.826826923 | V | A | 4.56167E-08 | m2 |
| A | 0.00002827 | m2 | A | 0.00002827 | m2 | P | 41800000 | Pa |
| a | 1408.833387 | m/s | a | 1384.79 | m/s | Pb | 5000000 | Pa |
| ρ | 844.7857206 | kg/m3 | ρ | 841.59 | kg/m3 | Pr | 52000000 | Pa |
| **Q** | **0.000125822** | **m3/s** | **Q** | **0.000100283** | **m3/s** | ρ | 859.689 | kg/m3 |
| **Q** | **125.8215645** | **mm3/ms** | **Q** | **100.2826813** | **mm3/ms** | **Q** | **3.41403E-05** | **m3/s** |
| | | | | | | **Q** | **34.14032586** | **mm3/ms** |

The discrepancies between the three flow rates found in Table A-2 can most likely be attributed to the following:

- The strain gauge amplifier gain being incorrect, requiring the amplifier to be recalibrated.
- The large amount of vibration propagating through the system.

Although there are discrepancies between the flow rates, it must be noted that they are not orders of magnitude different from each other, and the test rig is most likely functioning accurately in its measurement of the flow rate through the injector.

### Testing Round 2

A curve plotting the change in voltage on channel 1 (blue) and channel 2 (red- only seen in recording 3) with time, for each of the 3 test runs is seen below in Figures B.27-B.29. In all 3 of the plots, a clear, consistent voltage fluctuation of channel 1 is visible. This perturbation is the vibration measured after each injection of diesel fuel into the measuring tube.

Even though a voltage is recorded from the pressure transducer in test run 3 (see Figure B.29) the reading does not show any fluctuation during the firing of the fuel injector. It is therefore discarded in the analysis.

It must be noted that all three of the test runs record the strain gauge voltage as a negative. The reason for this most likely has to do with the calibration of the data logger or the strain gauge amplifier. Therefore, for the analysis, the amplitude of the voltage is used.

The increase in the rate of injection can clearly be seen in Figure A-5 to Figure A-7 below. Counting the number of perturbations per second in the Figures, it is seen that test run 1 averages 0.9 injections per second, test run 2 averages 1.2 injections per second, and test run 3 averages 2.8 injections per second. These numbers correlate well with those in Table A-3 below, where the injection frequency settings are shown. The average voltage for each of the curves is also given in Table A-3 and it can be seen that the magnitude of the voltage is similar for the test run 1 and 2, but is significantly larger for test run 3.

**Table A-3: Average Flow Rates for Each Test Run**

| Flow Rates (l/s) | | Voltages (V) |
|---|---|---|
| Theoretical | 0.03414 | |
| Test Run 1 | 0.41803 | 0.10641 |
| Test Run 2 | 0.40434 | 0.10267 |
| Test Run 3 | 0.53972 | 0.14050 |

By studying Figure A-8 to Figure A-10, it can be seen that the magnitude of the injection pulses are just below 0.11V for test run 1. The magnitude increases slightly for test run 2 (although, the average of the recorded perturbations actually has a slightly lower voltage magnitude), and then, for test run 3, the magnitude is greater than 0.11V. The increase in magnitude is more clearly visible in Figure A-5 to Figure A-7 which indicates a single injection pulse for each run. It seems therefore, that the injection magnitude increases with an increase in the injection frequency.

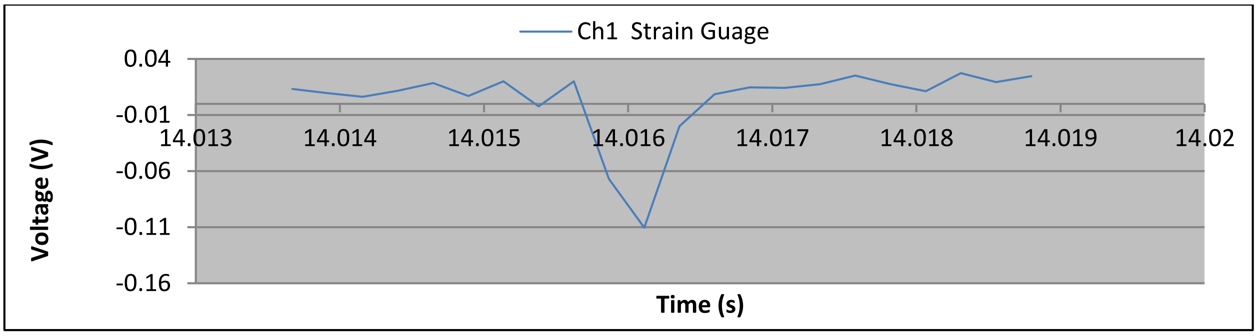


**Figure A-5: Single Pulse - Test Run 1**

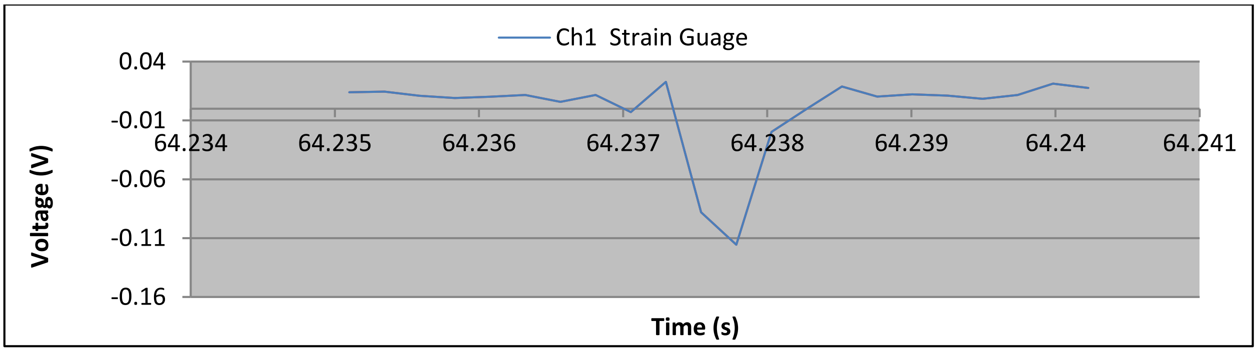


**Figure A-6: Single Pulse - Test Run 2**

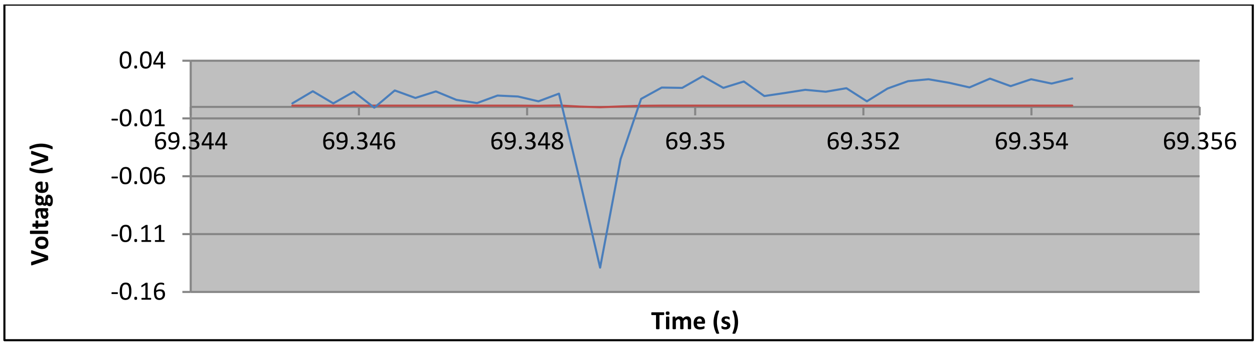


**Figure A-7: Single Pulse - Test Run 3**

### Individual Injection

The shape of the curve for test run 1 and 2 (Figure 5-5 and Figure 5-6) is very similar in that there is a distinct change in the gradient of the curve halfway through. However, in test run 3 (Figure 5-7), the curve is mainly symmetrical in shape, showing a far more uniform recording of the pressure pulse. With so few data points (because of the recording frequency being 4.096 kHz), it may simply be that the symmetrical shape of the curve would change if there were more data points on the curve measuring the injection.

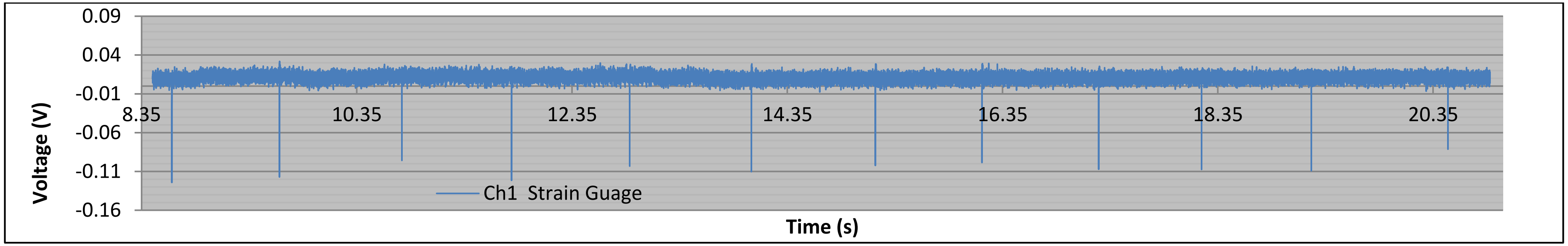


**Figure A-8: Test Run 1**

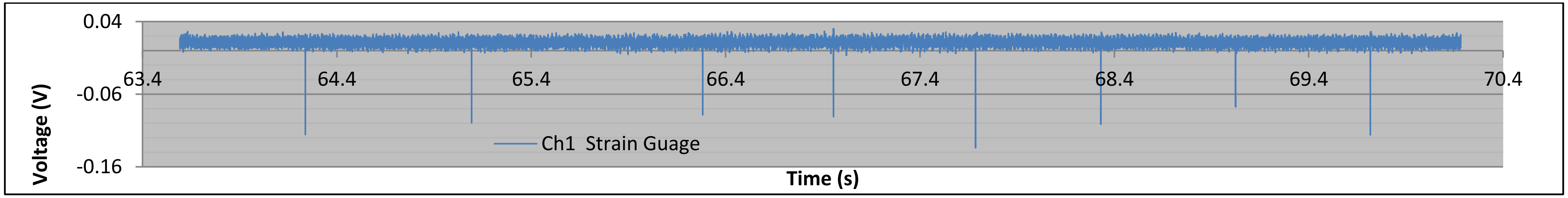


**Figure A-9: Test Run 2**

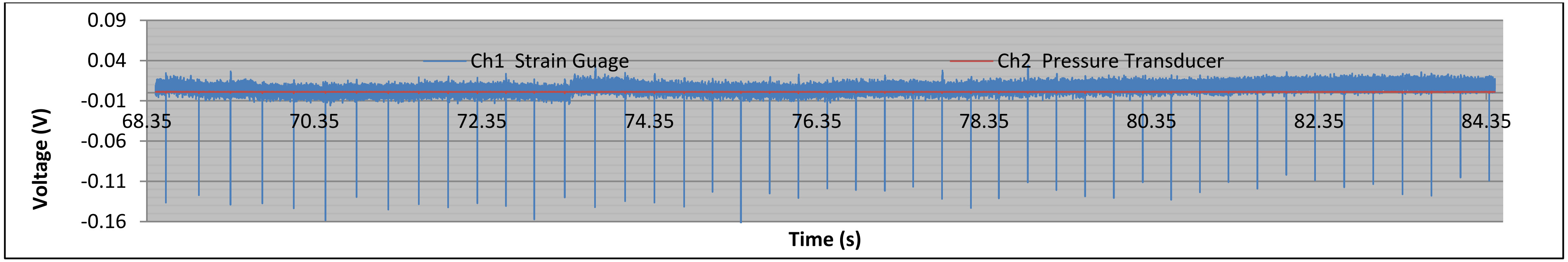


**Figure A-10: Test Run 3**