DIAGNOSTICS OF FUEL INJECTION SYSTEMS IN A CI ENGINE FUELLED WITH BIODIESEL BASED ON VIBRATION RESPONSES

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Copyright Statement

ABSTRACT

In recent years, serious restrictions on diesel emission levels, combined with price instability and a significant increase in imports, has forced researchers to look for alternatives to this fossil fuel. Biodiesel is widely accepted as an alternative because it can be used in diesel engines without any substantial modifications and produced by sustainable resources. However, there are serious gaps in available knowledge regarding the effects of biodiesel blends on engine fuel injection systems and the engine combustion process. Therefore, this research focuses on the investigation into such effects through a vibration analysis of fuel injection systems in order to achieve nonintrusive quantitative diagnosis and hence condition monitoring of CI engines.

Having identified the specifics of technique gaps by a comprehensive literature study, this research firstly, investigates the dynamics of the fuel injection system with a CI engine running on biodiesel blends as fuels. This is achieved by numerical modelling analysis and experimental studies, which paves ways for using vibration response of fuel injection to diagnose the dynamic behaviour of different fuel properties. Then it investigates the of the change dynamic behaviour of fuel injection on engine combustion process. Finally, it explores the diagnostics of engine valve train clearance faults with an engine running with biodiesel and biodiesel blends based on engine fuel injection vibration responses.

A mathematical model has been developed and used to simulate the behaviour of the fuel injection system, including the fuel delivery and injector needle valve motions. It has concluded that the high pressure dynamic forces within the injection system will be affected by fuel properties such as fuel density, viscosity and bulk modules. The simulation results demonstrated; (i) that, the injector pressure is higher than that of the fuel injection pump, whose amplitudes are about 10% higher for biodiesels compared with petro-diesel; (ii) the levels of the pressure forces applied to the delivery valve and injector needle valve are also higher for biodiesel blends and (iii) nearly 1° (cam shaft) advance in the times of fuel injection rates and valve impacts with biodiesel and biodiesel blends. These predictions are confirmed by experimental results obtained by injection line pressures and pump vibrations and in-cylinder pressures.

Diesel engines are particularly prone to the engine combustion process primarily due to a fault in the fuel injection system and an abnormal clearance valve train conditions. The high-signal to noise ratio pump vibrations obtained from the pump body can be easily used for detecting and diagnosing faults from fuel injections. In the meantime, the research has also established that the pump vibration signals can be also used to recognise valve train diagnostics with medium effort of signal processing. It has found that the vibration levels become higher, due to the faults as a consequence of additional fuel supply to compromise the loss of overall power caused by poor combustion performance on the cylinder with an increased valve clearance. Moreover, B20 and B40 exhibit the similar changes with that of petro-diesel in the proposed high frequency envelop amplitudes (HFEA) whereas B100 shows less increased values. However, the pressure measurements are not very clear in representing these small changes in valve clearances for both the exhaust and inlet valves.

Compared with head vibration signals, which also can indicate the faults by a reduced level of vibration due to an effect combined reduced valve movement stroke with gas flow dampening, the pump vibration signals uniformly show the injection events and allow combustion uniformity between different cylinders to be diagnosed using a single transducer, whereas it may produce less accurate diagnosis by the head vibrations because of the close overlap of combustion and valve impact responses which needs complicated methods to be separated.

Declaration

No portion of this work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

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List of Abbreviations

UoH,	University of Huddersfield
CI	Compression ignition
BDC	Bottom dead centre
TDC	Top dead centre
CM	Condition Monitoring
CO	Carbon monoxide
DAQ	Data acquisition system
EVC	Exhaust valve close
EVO	Exhaust valve open
IVC	Inlet valve close
IVO	Inlet valve open
FIP	Fuel injection pump
RM	Root mean square
WCO	Waste cooking oil
HHR	Heat release rate
IAS	Instantaneous angular speed
AE	Acoustic emission
D100	Petro-diesel fuel
B100	Biodiesel fuel
B20	20 % Biodiesel & 80 % Petro-diesel
B40	40 % Biodiesel & 60 % Petro-diesel

RMS	Root mean square
DAQ	Data Acquisition
IMP	Indicated mean pressure
HFEA	High frequency envelop amplitude

List of Notations

d_p	Displacement of pump plunger
v_p	Velocity of Pump plunger
C_q	Discharge coefficient
ρ	Fuel density
ρ_0	Initial fuel density
P_P	Pressure of pump plunger
B_p	Bulk modules variation of pump plunger
B_d	Bulk modules variation of fuel delivery valve
B_l	Bulk modules variation of fuel injection pipe
B_n	Bulk modules variation of fuel injector
A_{ax}	Section of delivery valve area
V_{dv}	Volume of delivery valve
Q_{Pd}	Fuel rate of delivery valve
d_d	Displacement of delivery valve
f_s	Spring forces of fuel delivery valve
k_{ds}	Spring stiffness's of fuel delivery valve
m_{dv}	Mass of fuel delivery valve

v_{dz}	Velocity of fuel delivery valve
P_d	Pressure of fuel delivery valve
P_l	Pressure of fuel injection pipe
Q_l	Fuel injection rate of fuel pipe
d_{nz}	Displacement of fuel injector needle
P_{ing}	Pressure of fuel injection
P_{cy}	In-cylinder pressure
Q_{ing}	Fuel injection rate
V_{sac}	Volume of fuel injector needle
v_n	Velocity of fuel injector needle
m_n	Mass of fuel injector needle
f_n	Spring forces of fuel injector needle
k_{ns}	Spring stiffness's of fuel injector needle
A_p	Plunger area of fuel injection pump,
B_S	Boost stroke,
L_P	Length of plunger

List of Publications

- Aburass, Ali, Zhen, Dong, Gu, Fengshou and Ball, Andrew (2013) Combustion Diagnostics of a Diesel Engine with Biodiesel Fuels based on Vibro-acoustics and In-Cylinder Pressure Measurements. Computing and Engineering Annual Researchers' Conference 2013: CEARC'13. University of Huddersfield, pp. 13-18. ISBN 9781862181212

- Aburass, Ali, Yangchun, Guo, Tie, Wang, Fengshou, Gu, Ball, Andrew and Brown, D.R. (2014), Investigation of the Effect of Biodiesel Blends on Fuel Injection Pumps based on Vibration and Pressure Measurements. In VETOMAC-X 2014, University of Manchester, UK.

- Madamedon, Misan, Gu, Fengshou, Aburass, Ali and Ball, Andrew (2016) Online Estimation of Engine Driveline Dynamic Properties. In: International Conference for Student on Applied engineering, 20-21st October 2016, Newcastle

CHAPTER ONE

1 INTRODUCTION

This Chapter presents a brief background of the research conducted in this research work and an overall introduction to the importance of biodiesel in transport sector and industries, including the physical characteristics of biodiesel, engine performance with effects engine emission characteristics. Also in this chapter diesel engine condition monitoring with the general research motivation is presented together with the aims and objective of the research study. Finally, a thesis outline is given with a brief synopsis of the content of each chapter.

1.1 Research Background

The diesel engine is used almost everywhere on the planet: in land and sea transportation, for construction equipment and powering industrial, as a generator supplying electricity, as the motor force behind many pumping systems, and so on, see Figure 1-1. Recent significant technological developments of the diesel engine include the turbochargers and superchargers to raise the power output and engine responsiveness under load and changes in the engine combustion chamber such as pistons and train valves designs to increase fuel burning effectiveness. However, due to the limited resources of fossil fuels in the world, fluctuating costs and concern over security of supplies, finding alternative fuels is now a necessity. Environmental concerns and commercial competition demand ever greater efficiency, effectiveness and fuel economy from modern diesel engines. E. g., increasingly strict environmental regulations require reduced emissions from diesel engines for improved environmental protection. Combined with increased public sensitivity to the environmental problems created by pollution due to the fossil fuels, alternative solutions to fossil fuels are increasingly being considered.

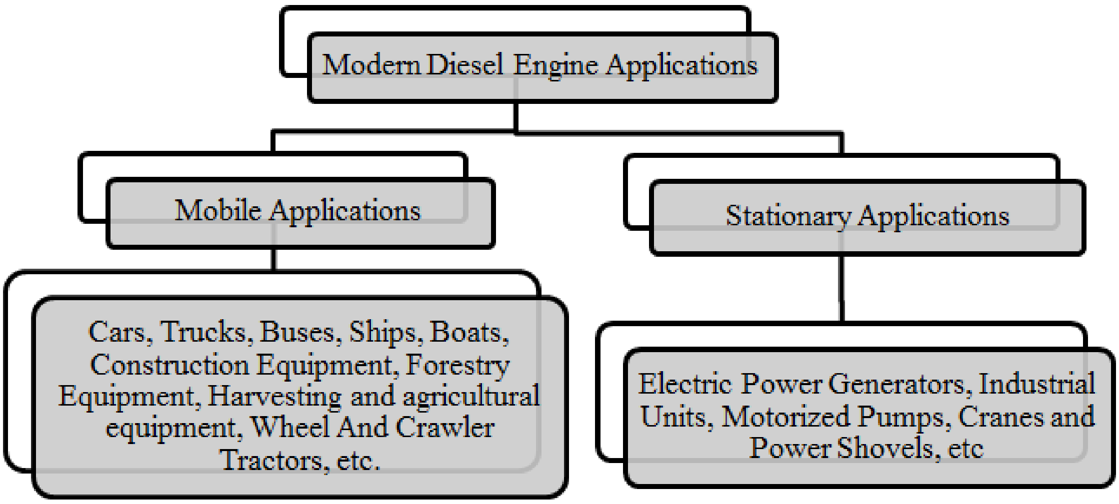


Figure 1-1 Modern Diesel Engine Applications

Unstable the fuel expenses and rising energy demands, combined with growing concern over greenhouse gas emissions, have led to increased interest in the use of renewable fuels to help meet increasing worldwide fuel demand and reduce atmospheric CO2 emissions from transportation sources [1, 2]. In recent years, there has been increased demand for energy, for example, electricity generation increases in world 24 % from 2013 to 2020 as shown Figure

1-2. The renewable fuel increases from 11 % in 2011 to 16 % in 2020 [3]. In response the renewable fuel increases in this decade from 11 % to 16 %. Thus over the last few years serious efforts have been made to use different sources for fuel in existing diesel engines. The feedstock used in the production of biodiesel is varied but in Europe, the most common feedstock is waste cooking oil (WCO). As large amounts of waste cooking oils are illegally dumped into rivers and landfills, causing environmental pollution, the use of waste cooking oil to produce biodiesel as a petro-diesel substitute offers significant advantages because of the consequential reduction in environmental pollution [4].

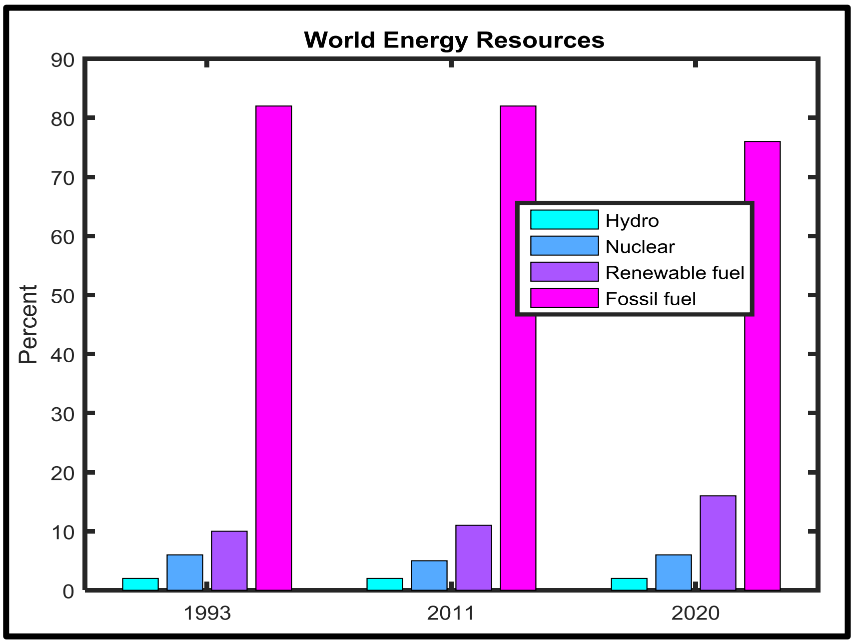


Figure 1-2 World energy resources [3]

It is well known that a huge quantity of the animal fats and waste cooking oil is available throughout the world, that's especially in the developed countries and that it is one of the most economical choices from which to produce biodiesel. Since one of the major concerns on biodiesel production is the price of feedstock, utilization of waste cooking oil significantly enhances the economic viability of biodiesel production and the Oak Ridge National Laboratory has confirmed that waste greases, animal fats and waste vegetable oils can provide biodiesel at relatively attractive prices [5]. Additionally, the waste cooking oil use as a biodiesel source which has the potential to reduce the particulate matter, CO2 and other greenhouse gases as the carbon contained in biomass-derived fuel is largely biogenic and renewable. A discussion of waste cooking oils is provided in Section (2.1.2).

1.2 Diesel Engine Running with Biodiesel Fuel

Increasing concerns regarding stable, safe and environmentally friendly energy sources, means the promotion of biodiesel in the transport sector is a priority on the world political agenda [6]. Biodiesel fuel and normal diesel have very similar of thermodynamic properties, whereas some differences at physical properties such as viscosity, density and bulk modulus do exist, [7-10] [11, 12]. However, these physical properties powerfully affect fuel injection system such as performance of fuel injection pump, pressure of fuel injection, fuel injection rate and air-fuel mixing characteristics. Also these effects extend to engine performance and engine emission characteristics as their relatively high density and viscosity biodiesels result in fuel filter of the pipe clogging and flow rate variations [13, 14].

Few researchers have been investigated the effects of the physical properties fuel of biodiesel and biodiesel blends on the engine fuel injection system performance characteristics, fuel injection system operation and air-fuel mixing behaviour [15], [16] [17]. These authors reported that an engine using highly viscous biodiesel and biodiesel blends could not develop its rated power that the fuel injection pressure increased with in-cylinder pressure, advancing the time at which the fuel was injected and thus advancing fuel ignition. This phenomenon was explained on the basis that viscosity of the biodiesel fuel was higher than normal diesel.

The literature review highlights the lack of research into the effects of biodiesel properties such as density and viscosity on high pressure fuel injection system and internal combustion [18]. How to maintain competitive fuel economy, refinement and specific power while at the same time keeping vibration, noise and exhaust emissions at acceptable levels is a major challenge for biodiesel fuels and will require a thorough programme of investigation, monitoring and optimisation of engine diagnostics. Investigation is required to study and understand dynamic fuel injection characteristics at different operating conditions when engine running with different biodiesel blends fuels. The lack of numerical and experimental investigations to quantify such effects [19, 20] needs to improve..

1.3 Diesel Engine Condition Monitoring

Condition monitoring and fault diagnosis is the science of determining the condition of a machine from measured parameters to determine the presence of faults or causes of unwanted effects, preferably before they significantly affect machine performance. The diesel engine normal operating can give many of hours of uninterrupted service. Nevertheless, if an engine fault variation, this fault tends to be fairly rapid and can lead to major failure, this can be cause costly of damage to property and even loss of life, and thus it is desirable to detect such faults at the earliest time possible. In general, researchers consider that diesel engine faults should be categorised according to their location in the engine system, such as fuel injection system faults, cooling system faults and lubrication system faults. These may be further divided into mechanical faults and combustion faults depending upon there are their effect on the engine components and the processes.

However, diesel engine condition monitoring (CM) techniques is varying largely according to the machines or dynamic processes being monitored and the objectives of the maintenance. CM takes maintenance an extra step by enabling the maintenance engineer to see a fault developing much sooner than would be possible with simple visual or aural inspections. In recent years, use of CM techniques for IC engines has led to reliable nonintrusive methods for engine diagnosis. For diesel engines specifically some methods are more suitable than others and for every component another monitoring method can be more applicable. That is why the division into different methods is made according to the different components to be monitored. Every component has its own parameters, faults and failure consequences.

For diesel engines, specifically, some CM methods are more suitable than others and for every component more than one monitoring method may be applicable. That is why the division into different methods is made according to the different components to be monitored. Every component has its own parameters, faults and failure consequences. The classification of faults is roughly the same in all literature, see Figure 1-3, where the faults are classified according to engine system components, fuel injection system and engine internal combustion. It can be seen that valves have the lowest life (highest percentage of faults) in diesel engines [21, 22].

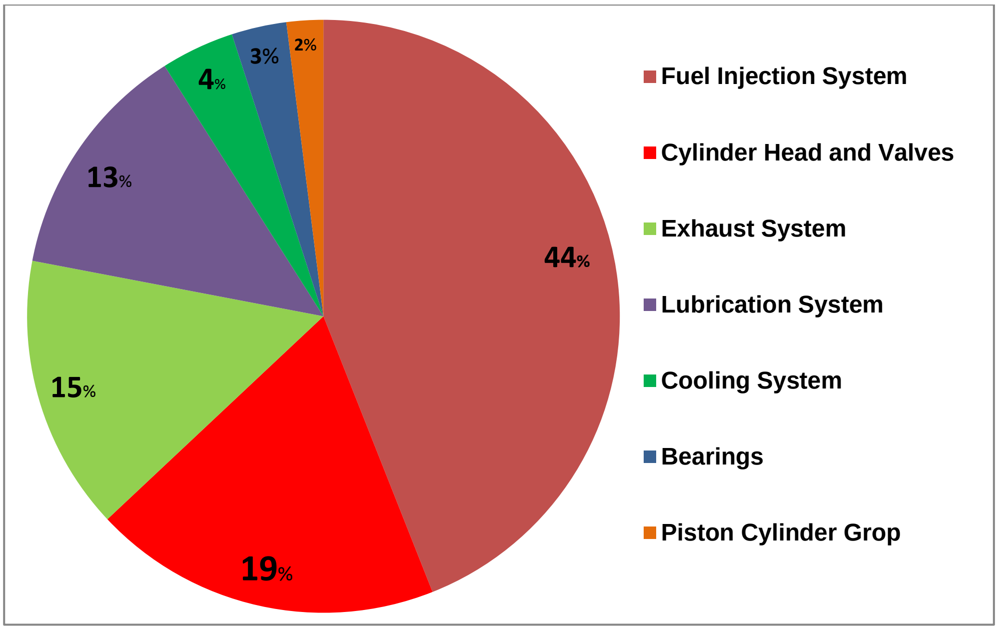


Figure 1-3 Principal percentage faults of diesel engines [22]

Diesel engine fuel injection is playing an important role in the development of the combustion chamber, and even minor faults in the fuel injection equipment can cause a major loss of efficiency of engine combustion and an growth in engine emissions and noise [23]. In particular, the valves in an internal combustion engine play an important role in engine performance while being subject to high temperatures and gas pressure impulses. It is, thus, no surprise that, in the failure analysis of a valve train, valve failures are the most common problem. The major causes of valve failure are distortion of the valve seat, deposits on the valve, reduced tappet clearance, burnt valve and wear. [24-26].

The application of CM is an on-going progress and its application can be traced back to the earliest monitoring of engine condition. Initially the human senses of looking, listening, touching and smelling were the sensors used to monitoring the condition of machines and are still very useful for fault detection [27]. Today, advanced CM and fault diagnosis systems consist of sets of sensors (e.g. accelerometers) detecting relevant properties of the machine (e.g. its vibration) and feeding the signals obtained to computerised analysis that can detect and identify incipient faults and so ensure that the machine remains in good condition. Many researchers and manufacturers have paid close attention to developing a variety of CM methods or systems appropriate for a wide range of machinery. To keep abreast of technical developments and meet stringent environmental legislation, it is necessary to develop more efficient, reliable, robust and economical CM systems for diesel engines [27].

1.3.1 Vibration Condition Monitoring

Diesel engines are now far too complex to be monitored using only the human senses, today measurement of acoustic emission, airborne acoustic; engine temperature, fuel injection pressure, and cylinder head vibration are widely practised. Most recent studies to better understand and monitor the mechanism the important parts of diesel engine used non-intrusive vibration based CM. The vibrations generated by the engine processes such as fuel injection and engine combustion, are used to indicate the engine condition.

This main purpose of CM is to use information extracted from the vibration response of a machine to measure of its health, to detect and identify faults at an early stage of their development and to quantify likely time to failure. A change in the vibration response not only indicates a change in machine conditions but can also point directly to the source of the change. The vibration technique is non-intrusive and its ability to diagnose a wide range of mechanical faults means that vibration monitoring techniques are in common use in many industries. However, condition monitoring, fault detection and fault diagnosis, are different terms sometimes used improperly. CM and fault detection generally refer to the evaluation of the state of a machine and the detection of an anomaly. Fault diagnosis is a more rigorous analysis and requires the identification of the component or process that causes the machine's deviation from the normal state

Traditionally, trending analysis has been used to predict the likelihood of incidence of future actions, the time domain and time domain parameters analysis the vibration response, that's can be monitored and plotted over time, and if the magnitude exceeds a certain critical level then remedial action is taken.

However, the vibration response of a machine process, although produced by the individual mechanisms, that's can be affect by their assembly, interaction and. Installation. By comparison of the actual frequency amplitude beside amplitude from a healthy condition, the condition status of the machine is normal, acceptable, unacceptable may can be determined.

The vibration response uses for diagnostic, detecting and identifying faults in diesel engines has attracted much interest in the research community in the past two decades and has been used in this research to investigate the fuel injection dynamic process and as a diagnostic for the engine combustion process. Since, it is possible to identify the vibration signatures of engine components, extracting that signature can provide information on component or operational factors that produce significant deviations within the indication.

1.4 Research Motivation

Research in the area of alternative fuels has resulted in biodiesels becoming more economically feasible by lowering production costs and increasing the energetic yields from various feed stocks. However, research characterising the performance of these fuels, in all possible diesel applications, has previously been lacking, because still not enough research to monitor the fuel injection process with internal combustion engines which are complicated mechanical systems with many rotational and reciprocal component, has occurred That's with advanced fuel injection and fuel injection pressures have increased which has made it even more important to investigate the comparative performance of biodiesel and biodiesel blends on fuel injection and combustion characteristics and in the presence of engine combustion faults with these fuels behaviour.

Most studies of biodiesel fuel have concentrated on the engine performance measured using emissions, power output, specific fuel consumption, thermal efficiency [28], etc. Long term effects have yet to be studied. Assessment of the impact of these fuels with different engine operating parameters on engine fuel injection system life is extrapolated from short term trials, with little weight given to the maintenance problems that might arise with these changes.

Increasing use of renewable fuel in CI engines has led to a wide range of challenges demanding immediate attention. The first is the engine fuel injection system which needs constant monitoring. This crucial activity is required to ensure optimum performance and minimum impact on the environment by reducing emissions to bare minimum levels and so ensuring reliability of engine fuel injection components. Many researchers have investigated the effects of biodiesel on fuel injection pressure, and injection parameters have - to maintain engine performance - advanced injection timing and high pressure compared to normal diesel fuel [17] [29] [30], The reason for this was reported by Agarwal and Dhar [31] that higher fuel injection pressure gave a longer spray tip, greater penetration and larger spray area compared for an identical elapsed time after commencing injection. These researchers tested and compared biodiesel blends with normal diesel.

Nevertheless, these studies were carried out over only a limited range of diesel engine operating conditions. Typically, a diesel engine will operate at various engine speeds under different loads and the investigation of the effects of changes in density and viscosity of the fuels needs to be extended. Common effects of biodiesel fuel are varying fuel injection pressures and in-cylinder pressure and these are studied in this research using vibration signals produced by the engine components. Vibration measurement will be used to enhance the understanding of changes in the fuel injection and combustion process mechanical with different fuels. This will be achieved by the diagnostic analysis of the complex vibrations obtained from transducers placed on the fuel injection pump to monitor the fuel injection system and cylinder head vibration to monitor the combustion process for the engine fuelled by biodiesel and normal diesel.

However, few researchers have monitored the fuel injection system of a diesel engine fuelled by biodiesel and normal diesel using vibration measurement on the injector and fuel injection pipe. Changes in the high pressure fuel injection parameters change the internal chamber pressure, affect engine combustion and may affect the engine life and the maintenance requirements. That's when the ever increasing demands for greater fuel efficiency and engine performance is forcing researchers to better understand the mechanisms and effective parameters of fuel injection dynamics and internal combustion processes. Engine internal combustion for burning fuels is one of the most important dynamic processes; it controls the engine performance and engine emission characteristics in addition to engine durability.

Changes of fuel injection parameters may affect diesel engine life and maintenance requirements. Due specifically to the effects increase with valve train clearance on internal combustion. However, a numbers of gaps have been identified in the knowledge of how biodiesel and biodiesel blends impact on the behaviour of fuel injection systems and combustion characteristics, particularly detection of faulty clearance of the internal combustion valves.

Various feature extraction techniques are used to obtain diagnostic information. Vibration analysis is a very powerful and reliable technique for monitoring the machine under different operating conditions and is now widely used in industry because it is non-destructive in nature and allows sustainable monitoring without interfering in the process. A large number of signal processing techniques are available to be used in order to extract interesting information from a measured vibration response.

This research study seeks to use vibration based CM techniques for diagnosis and assessment of the fuel injection system of diesel engines running under biodiesel fuels. This research also explored to diagnosis engine combustion by analysis fuel injection vibration. This contribution will extend current state-of-the-art techniques to improve the understanding of fuel injection vibration and combustion-induced vibration in operational diesel engines.

1.5 Research Aims and Objectives

The overall aim of this research is to develop techniques for the nonintrusive CM diesel engine fuel injection systems based on the analysis of measured non-stationary vibration signals, which allows the study of the effects of biodiesel and biodiesel blends on the precise fuel supply equipment including the high pressure of fuel injection pump and fuel injector when subject to changes in fuel physical properties and thereby provides approaches to improve and diagnose the equipment including its accompanied combustion.

To fulfil this research, aim a number of critical objectives are identified and implemented with high priority, which are summarized as the following:

Objective one: To gain understandings of the relative physical properties of petro-diesel and biodiesel blends, including such parameters as fuel density, viscosity, bulk modules, heat value and their associated temperature characteristics.

Objective two: To analyse influences of different fuels on the dynamics of engine fuel injection using FIP and fuel injector pressure measurements during steady engine operation. Fuel injection parameters such as peak pressure, injection time and injection duration have been studied to understand the different impact of biodiesel blends on the fuel injection dynamics.

Objective three: To have a full knowledge of different techniques capable of nonintrusive monitoring and diagnosing engine conditions by reviewing the literatures.

Objective four: To gain more insight into the influences on the dynamics fuel injection by developing a mathematical model of the high pressure injection equipment and thereby carry out systematic numerical simulation studies of the fuel supply equipment operated under engine running with biodiesel and biodiesel blends.

Objective five: To obtain the vibration characteristics of the fuel injection equipment, and investigate effective methods for analysing the non-stationary vibration signals for CM and diagnostics, which is based on the mechanical impacts within the structure of the engine fuel injection equipment as related to the different fuels.

Objective six: To study and understand the consequence of fuel injection dynamic behaviour changes with biodiesel and its blends on engine combustion process. In-cylinder pressures and engine vibration have been used to measure quantitatively the effects of biodiesel on engine combustion processes.

Objective seven: To further verify and improve the proposed online condition monitoring techniques to diagnose combustion changes due to valve train faults by analysis fuel injection pump vibration.

Objective eight: To evaluate the performance of vibration based engine detection of abnormal clearances in the valve train, with the engine fuelled with petro-diesel and biodiesel blends. In-cylinder pressures and engine vibration have been used to measure quantitatively the engine combustion process for the different valve train conditions with the different fuels.

1.6 Organisation of Thesis

To address the research subjects involved in achieving the objectives, this thesis is organised into nine correlated chapters. For readability, an outline of the content covered in each chapter is provided as follows:

Chapter two:

Following the establishment of research objectives in this chapter, Chapter two presents a review of the literature on biodiesel characterisation and emission characteristics. The main fuel properties, such as density, viscosity, bulk modulus and heat of combustion, of normal diesel and biodiesel blends are presented, compared and discussed.

Chapter three:

This chapter describes various CM techniques of diesel engines. and the state of the are approaches based on different measurements including fuel injection pressure, in-cylinder pressure, instantaneous angular speed, air-borne acoustics, acoustic emission and general engine surface vibration are critically reviewed with highlighting their performances in monitoring and diagnosing engine combustions.

Chapter four:

This chapter describes the diesel engine CM based on vibration measurement made on the fuel injection system and combustion process vibration of diesel engine. Specifically, vibration analysis for diesel engine fuelled biodiesel and biodiesel blends is evaluated, which focuses more on the signal process methods that are developed to extract diagnostic information from noisy measurements.

Chapter five:

This chapter deals with mathematical models of fuel injection processes. A new model is developed based on the nonlinear impact mechanisms involved in the fuel injection equipment of using different fuels: normal diesel, biodiesel and biodiesel blends. This model can explain the effect on the fuel injection pump and fuel injector of using biodiesel and allows predictive study of the effects of biodiesel on the combustion process based on fuel injection vibration responses induced by the impacts.

Chapter six:

Chapter six gives a detailed description of the experimental facilities (including test rig and instrumentation) used for testing engine and fuel injection system characteristics with different biodiesel blends and normal diesel. The details of measured parameters, data acquisitions system and application software are provided. Furthermore, the test procedures are described in rationing the methodology of the steady engine operation test procedure; clearance valves test procedure and fuel injection system procedure.

Chapter seven:

This chapter presents the effects resulting from the use of different biodiesel blends on the high pressures at both the fuel injection pump and injector. The fuel injection pump vibration results are discussed and correlated with the measured injection pump pressure. Fuel injection pressure parameters such as peak pressure, injection duration and injection time are analysed and related to each biodiesel blend under different engine parameters. This chapter also presents the in-cylinder pressure and engine vibration under different fuels.

Chapter eight:

This chapter describes the results of the analysis of the measurements made on the fuel injection pressure, fuel injection pump vibration, engine vibration and in-cylinder pressure parameters in the presence of valve train clearance faults with engine running with biodiesel and biodiesel blends. Each valve condition discussed is related to each fuel test.

Chapter nine:

This chapter presents conclusions and suggestions for future work based on the findings of established in this research. The conclusions have been categorised in different sections for fuel injection system and engine combustion characterisation.

CHAPTER TWO

2 BIODIESEL CHARACTERISTICS

This chapter presents a comparative review on the properties of diesel and biodiesel. Waste cooking oil as a feedstock for biodiesel is focused on in this study. The essential relevant physical properties of diesel and biodiesel blends, such as density, viscosity and heating value are given discussed in association their potential effects on the dynamics of fuel supply equipment.

2.1 Biodiesel Fuel Characterisation

Most of the characteristics of biodiesel and biodiesel blends are similar to petro-diesel, then there are significant differences in many basic properties such as viscosity, density, bulk modulus and heating values [32, 33]. Biodiesel is produced by a process in industry refers to as esterification or trans-esterification: when the chemical properties of the base waste cooking oil are modified. Trans-esterification can provide engine benefits which include reduced viscosity, a complete removal of glycerine, a higher boiling point, a lowered pour point and a higher flash point [34]. For use in diesel engines, the properties of the biodiesel must meet the EN-14213 Europe specifications [35] and D-6751 United States specifications [36]. Elements of these are presented in Table 2-1.

Table 2-1 Standard specification biodiesel and diesel fuel

Property	**Units**	**EN-14214**		**ASTAM-D6751**	
		Diesel	Biodiesel	Diesel	Biodiesel
Specific Gravity		-	0.86-90	0.82 – 0.86	-
Viscosity	Mm/s	1.3 - 4.1	3.50 - 5.00	1.9 – 6.00	2 – 4.5
Calorific Valve	MJ/Kg	42.7	37 – 40		
Flash Point			120 min		130 min
Cetane Number			51		47
Iodine Value					120 max

The major shortcoming of diesel engine running with biodiesel is the detrimental effects caused by the higher viscosity of the biodiesel fuel [37] [38] [39] , see section 2.2.2. Also the diesel fuel density is a very important parameter that s has been correlated against other crucial engine performance parameters, such as heating value [40], see section 2.2.1. In this research these properties are studied by a comparison between biodiesel and biodiesel blends and normal diesel.

2.1.1 Feedstock of Biodiesel

The idea of using biodiesel fuel is Dr. Rudolf Diesel which he used the vegetable oil as a fuel dates back to 1895, that’s developed the first diesel engine with the purpose of running it on a variety of fuels [41].

The diesel engine established at the world exhibition in 1900 in Paris which is operating on oil extracted from peanuts. Meanwhile his death at 1913, his engine has been adapted to run based on petro-diesel fuel, and it was not until the 1970's that there was any substantial interest in biodiesel.

Today, biodiesel fuels have been commercialised in several countries, including France, Italy Austria, Germany, USA, Czech Republic, Spain, and the. Slovakia, Global biofuel production can be divided into three categories; ethanol, biodiesel and Hydro-treated vegetable oil as shown in Figure 2-1 which also shows that in 2014 the total world production of biodiesel was around 110 billion litres [42].

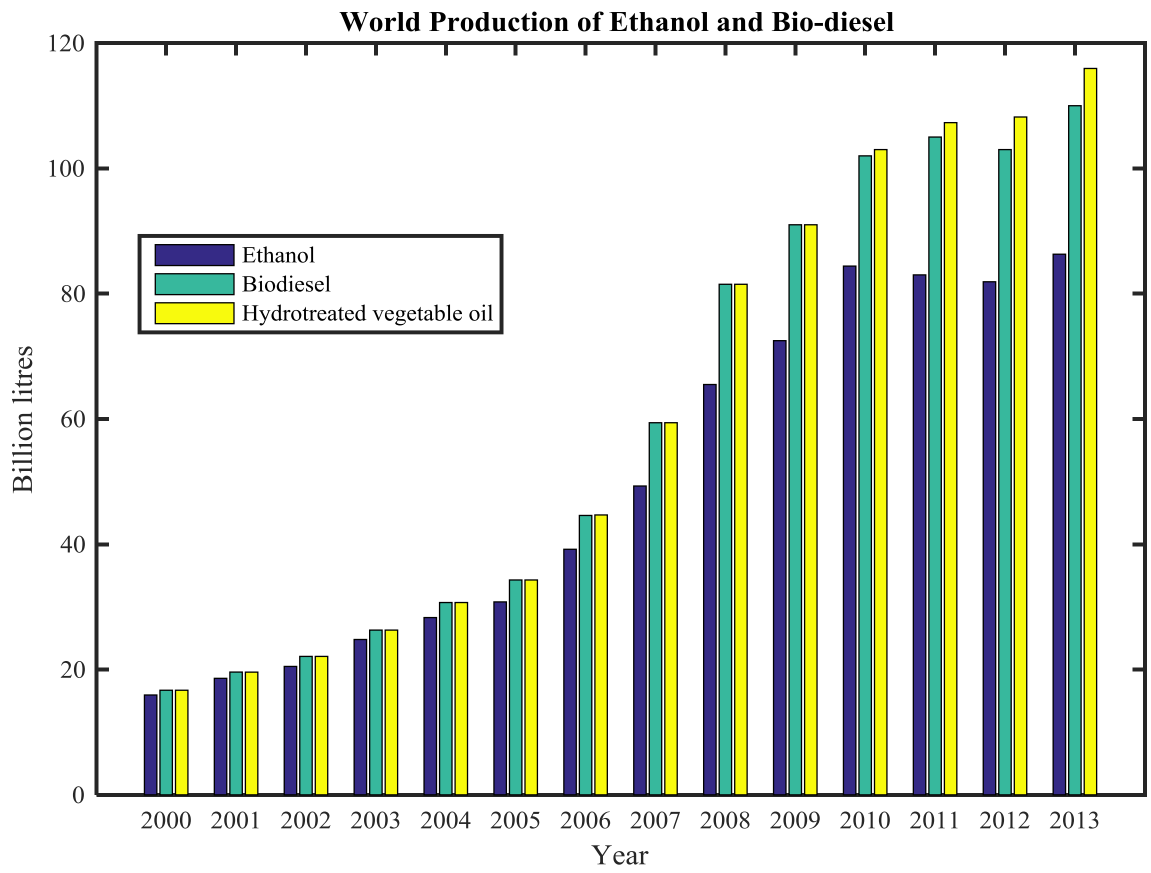


Figure 2-1 World Production of Ethanol, Bio-diesel and hydrotreated vegetable oil [42] [43]. [44].

2.1.2 Waste Cooking Oils

An economically feasible source for biodiesel is WCO or frying oils, also known as yellow grease. The high cost of biodiesel is the major obstacle to its commercialisation but waste cooking oils (WCO) is, potentially, a feedstock that is 2~3 times cheaper than edible vegetable oils [45, 46] [47], and does not compete directly with the growth of food crops. Vast quantities of WCO and animal fats are available throughout the world, specifically in the developed countries. Organisation of such fats poses and oils a major challenge because of removal problems and possible contamination of water and land resources. Even though some of this WCO is can be for soap production, a main part of it is discharged into the environment, landfills causing environmental pollution and illegally dumped into rivers [4, 48-50].

However, waste cooking oil is easy to collect from other industries such as domestic usage and restaurants and also cheaper than other oils. Hence, by using these oils as the raw material, we can reduce the cost in biodiesel production which lower the cost to produce biodiesel and assist in the prevention of environment pollution [51, 52]. The Energy Information Administration in the United States estimated that 100 to 200 million gallons of waste cooking oil is produced per day in USA, where the average per capita waste cooking oil was reported to be 9 pounds [5] [45, 53].

However, WCO is easy to collect from, e.g., restaurants, cafeteria and canteens and its cheapness relative to other oils means that the cost of biodiesel production can be significantly reduced while simultaneously preventing environment pollution [5] [54]. The United States Energy Information Administration estimated that 100 to 200 million gallons of WCO is created per day in the USA (120 to 240 million tonnes per year) and, on average, the annual per capita domestic production of WCO was 4 kg [55], [56]. In the EU, the total WCO production has been approximately 700,000-1,000,000 tonnes/year [49, 57].

2.2 Characterisation of Biodiesel Blends

To reduce the problems arising from the higher viscosity and density of the biodiesel, it is often used mixed with petro-diesel. The blends are usually designated B5, B10, B20 and B100 where, for example, B20 is 20% of B100 biodiesel by volume blended with 80% petro-diesel.

Many researchers have investigated the use of biodiesel blends in various diesel engines to determine effects on such performance characteristics as exhaust emission, energy output and thermal efficiency [58, 59] [60] [59, 61]. When the results were compared with petro-diesel a reduction in harmful exhaust gas emissions was obtained from B10 up to B100. It was also found that at maximum load the brake thermal efficiency of B20 was 25.2% which was significantly more than the figure obtained for petro-diesel which was 22.9%. This indicates that using the biodiesel bends improved diesel engine performance and efficiency [62, 63].

As stated above, differences in density, viscosity, heat value and bulk modulus have been reported for different biodiesel blends (WCOs) and these have been measured and compared with petro-diesel [14, 38, 64] These factors are those that most powerfully affect fuel injection pump, fuel injection rate, fuel injection pressure and injection duration which greatly influence engine performance and engine emission characteristics. This study includes an investigation of the physical-chemical properties of biodiesel blends to minimise any detrimental influences of these proprieties on engine combustion and the fuel injection system. This chapter reports an investigation of three biodiesel blends B100, B40 and B20 and compares fuel properties such as density, viscosity, and bulk modules with normal diesel. It also focuses on fuel property such as density, viscosity, and heat in each fuel B100, B20, B40 compared with normal diesel.

2.2.1 Density of Biodiesel

Fuel density is an important property of biodiesel fuel. It is defined as its mass per unit volume, while the specific gravity is the ratio of density of a substance to the density of water at 40C and 1 atm, but since the density of water under these condition is effectively unity, the two values are numerically the same to within 0.003%. Volumetric mass density is an important property of the fuel because it determines the mass of fuel that is compressed and burned in the combustion chamber [65]. The higher the fuel density the greater the mass of fuel that is injected into the combustion chamber, which can result in an increase in Hydrocarbons (HCs) and Carbon monoxide (CO) and decrease in oxides of nitrogen (NOx) and Particulate Matter (PM) in the exhaust emissions [66].

The densities of petro-diesel and three WCO biodiesel blends B20, B40 and B100 were measured experimentally and the results are shown in shown in Figure 2-2. The density of the biodiesel blends raised with an increase in the volume biodiesel fraction, these results agree with previously published literature [67, 68] [69] [17, 38, 70].

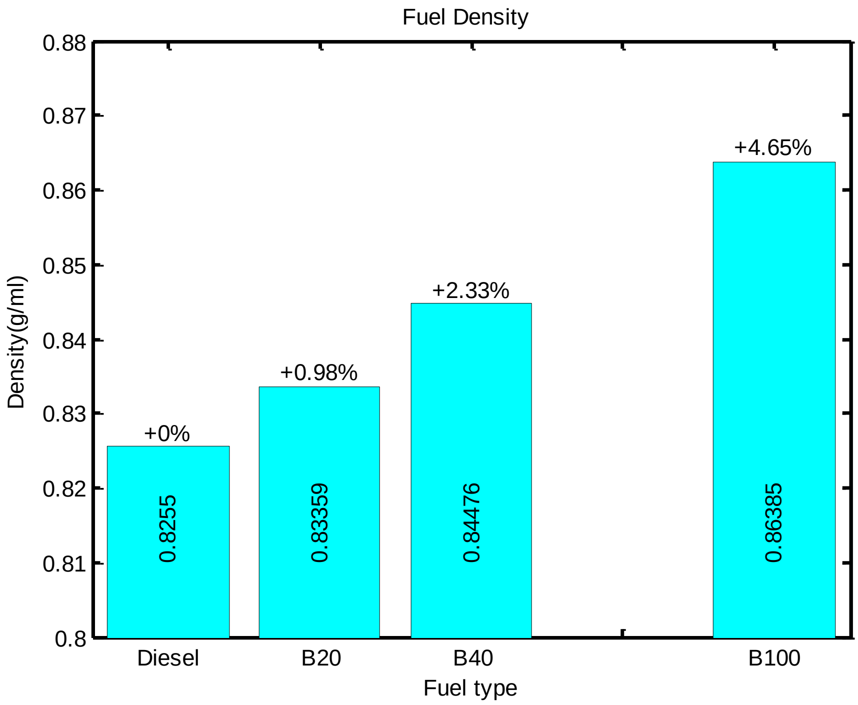


Figure 2-2 Density of biodiesel, biodiesel blends and diesel fuel

2.2.2 Viscosity of Biodiesel

Viscosity is the property of a fuel by virtue that's it offers resistance to flow. In important, the viscosity is decreases with increased temperature of a fuel which is can able to fuel more readily. This is especially important with lower temperature when higher fuel viscosity gives poorer atomisation of the fuel spray in combustion chamber which less than desirable operation of the fuel injection system, increasing carbon deposition on the fuel filter, demanding more energy from the fuel pump and increasing wear of fuel pumps and injectors [71, 72], [38, 72, 73]. Typically, the viscosity of a biodiesel is higher than the viscosity of petro-diesel and some researchers have reported that biodiesel viscosity can be up to 1.6 times that of diesel at 40^0C [74]. This ratio increases when the temperature is below 25^0C. Blending of biodiesel with diesel and preheating of biodiesel before injection into the combustion chamber which significantly improves the viscous characteristics [39] [39, 75].

The viscosity of the biodiesel has been measured; see the section 6-5-2. The results are shown in Figure 2-3. The kinematic viscosity of biodiesel increased with increasing biodiesel blend fraction, these results agree with previously published literature [76-78] [79].

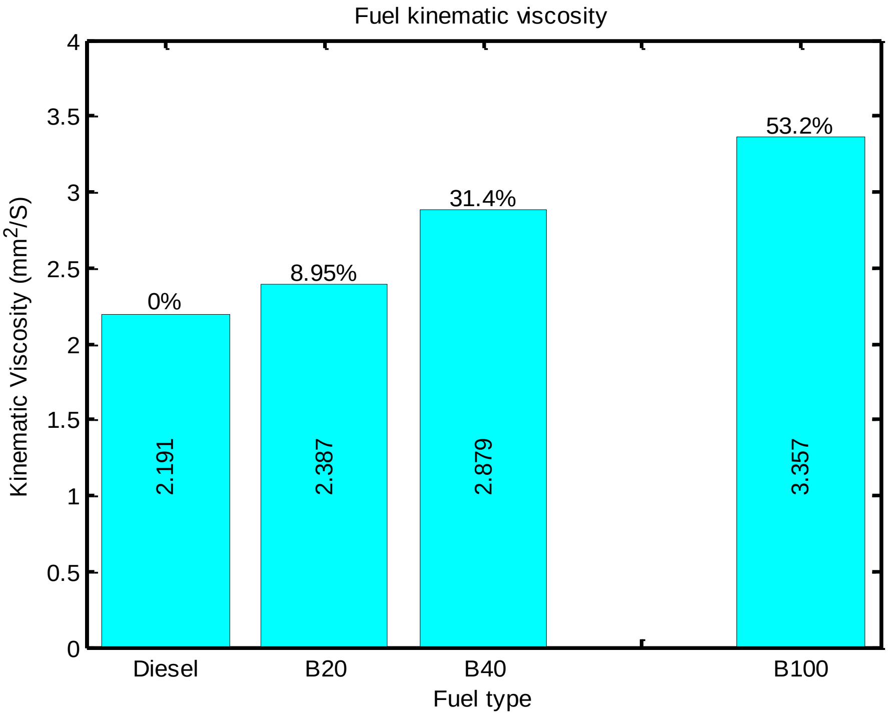


Figure 2-3 Viscosity of biodiesel, biodiesel blends and diesel fuel

2.2.3 Heating Value of Biodiesel

Heating value can be defined as the useful heat energy released by the combustion of unit mass of the biodiesel [80, 81]. It is one of the most important parameters for estimating engine design parameters [64, 82]. The heating value of fuel can be given in two ways: the higher heating value (HHV) or gross calorific value and the lower heating value (LHV). HHV refers to the heat released from the combustion of the fuel with any water generated remaining in a liquid state. LHV is the value used by most engineers for practical purposes and is based on any water being produced as steam [83]. Generally, LHV and HHV reduce the heat required for water vaporization.

Several researchers have reported the fuel heat value measurement resulting at using a bomb calorimeter, proximate and ultimate analyses. The conventional analysis is a complicated and time consuming process which requires specialised set-up, measurements and calculation procedures [84, 85]. One thing that can affect the e engine power is the heat valve of biodiesel when lower than normal diesel [63, 86, 87], this is one of the most important parameters for the design of processing engine systems and estimating performance engine parameters such brake specific fuel consumption, thermal efficiency and power torque [71], [57], [62], [71]. The combustion chemical energy of fuel shows in Figure 2-4.

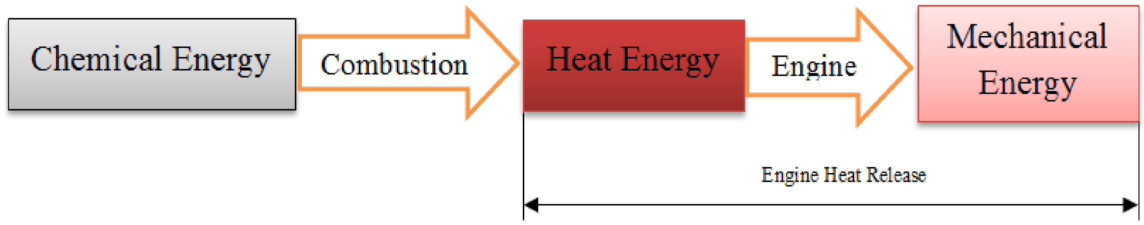


Figure 2-4 Engine internal combustion energy

To better understand the effects of the LHV of biodiesel on biodiesel blends the resulting calorific value has been measured using a bomb calorimeter, see Section 6.5.3. Figure 2-5 shows the calorific value of normal diesel is higher than for biodiesel and biodiesel blends. The lower calorific value of biodiesel may also require adjustment to the amount of fuel injected to compensate for the increased volume of fuel required to achieve similar power outputs to petro-diesel. The results obtained and effects on engine performance are discussed in Chapter Seven.

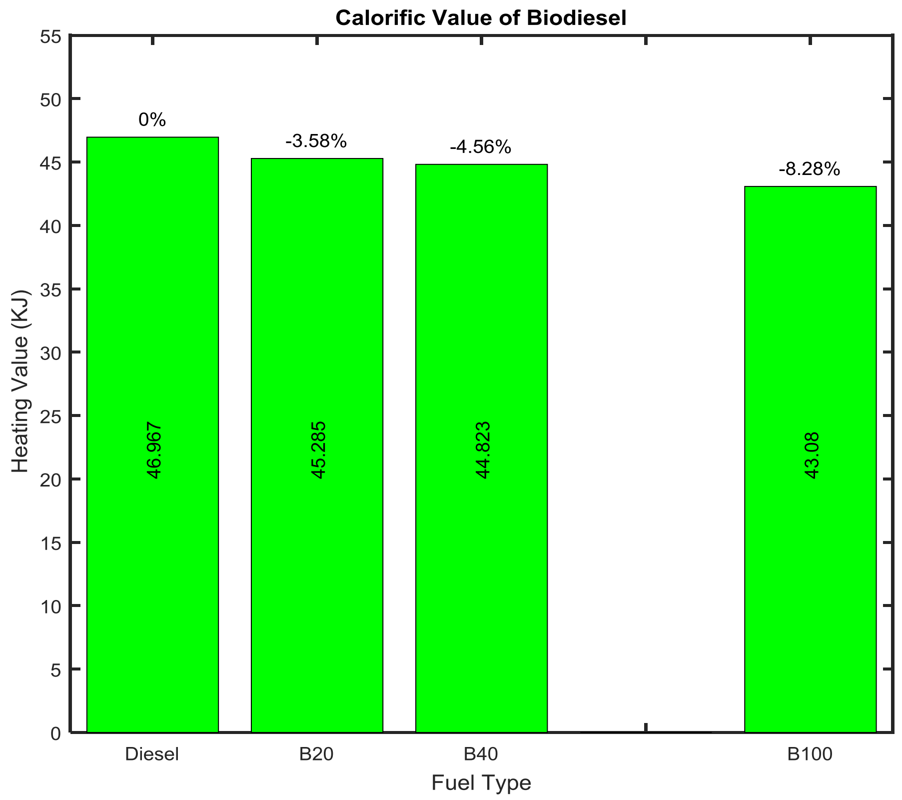


Figure 2-5 Calorific value of biodiesel, biodiesel blends and diesel fuel

2.2.4 Bulk Modulus of Biodiesel Fuel

The bulk modulus of a fluid is a measure of that fluid's resistance to uniform compression. In other words, bulk modulus is the ratio of a change in pressure acting on a volume of the fluid to the fractional change in fluid volume [88, 89]. Moreover, the bulk modulus will change with pressures applied to the fluid in a nonlinear way.

A number of researchers have investigated the fuel bulk modulus of alternative fuels [9, 89-91] and reported observable effect on combustion performances. However, little has been found on the effect on injection equipment. Nevertheless, a higher bulk modulus of biodiesel fuel (more than 30% compared with standard diesel) has been observed and this impacts not only the both fuel injection timing and variation of fuel injection pressure but also can apply addition dynamic changes to the fuel supply equipment.

Therefore, to depict the effect, this research investigates the pressures and low rates in different components including pump plunger, delivery fuel valve, pipeline of fuel injection and fuel injector for different biodiesel blends. This will give a quantitative assessment of the effect caused by changes in fuel bulk modulus, which will be detailed in Chapter 5 where numerical simulation results are presented.

2.2.5 Biodiesel Emission Characteristics

Current, more stringent future emission regulations have come into force, and as a consequence, the transport sector is undergoing rapid transformation in order to comply with these regulations. In addition, fossil fuel demand is continuously increasing globally [92], [93]. The main alternative fuels used in transport sector are biodiesel fuel, hydrogen, and Ethanol technology which are successfully recognised and commercialised developed countries. Nevertheless, the ethanol is limited and used only to spark ignition engines. Moreover, the result of using ethanol higher blends strengths of up to 15% cause problems.in fuel injection system.

A large number of studies have exposed that, biodiesel fuel is one of the most promising renewable fuel, alternative and environmentally friendly biofuels which can be used directly in diesel engines, with little or no requirement of engine modifications [18, 94-96]. Moreover, biodiesel has significant potential to reduce of engine emission such as CO2, CO, total hydrocarbons (THC) and PM emissions [56, 63, 97]. However, the literature review mostly exposed that, the engine running with biodiesel fuel is caused rises in emission of NOx [98-101]. During to engine combustion process the Oxides of nitrogen is chemical compounds formed by the combination of nitrogen and oxygen under extremely high temperatures.

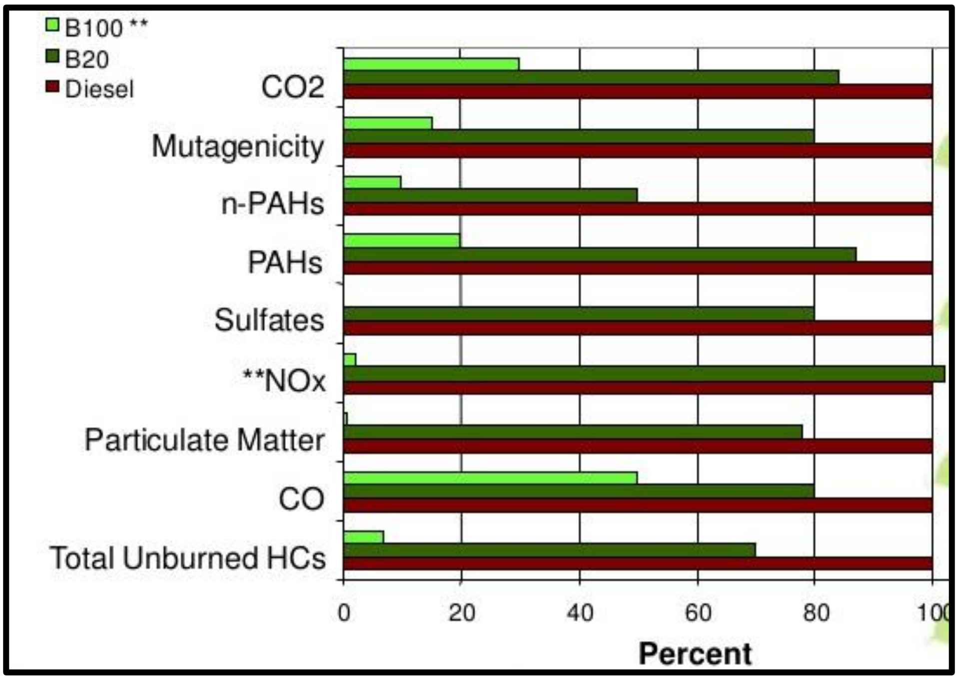


Figure 2-6 Overview of fuels emission such as biodiesel, B20 and normal diesel [98-101]

2.3 Summary

This chapter presents a review of the literature on biodiesel characterisation and emission characteristics. The main fuel properties, such as fuel density, viscosity, bulk modulus and heat of combustion, of normal diesel and biodiesel blends are presented, compared and discussed.

CHAPTER THREE

3 DIESEL ENGINE DIAGNOSTICS

This chapter describes the CM of diesel engines with highlighting various diagnostic techniques; such as fuel injection pressure, in-cylinder pressure, instantaneous angler speed, air-borne acoustic, acoustic emission and general engine surface vibration which are under investigation for many years in order to achieve accurate diagnosis both online and offline CM, as well as engine experimental studies.

3.1 Diesel Engine Condition Monitoring

The rapid growth of transportation systems mostly using internal combustion (IC) engines has led to a wide range of challenges demanding immediate attention. Maintenance and CM of an IC engine is a required activity to ensure minimum environmental pollution and optimum performance by restricting emissions to minimum levels and ensuring reliability of engine parts. Detecting the presence of faults and detecting the underlying cause as quickly as possible are the goals of engine CM.

The CM of diesel engines can be carried out on a continuous or periodic basis by the measurement of selected parameters. The application of CM and fault diagnosis strategies to a diesel engine is intended to increase its operational efficiency and reduce damage, spare parts inventories and breakdown maintenance. Most monitoring systems obtain information about operational engines from primary data and the use of signal processing techniques, to obtain vital information for the engine operator about the engine and its control system, before any failure occurs [27].

However, the detection of faults by CM can be done in two different ways; trend monitoring and condition checking. CM is best if the failure of the system is predictable and sufficient data can be gathered, i.e. the condition at one specific moment can be used to estimate the maintenance interval. In which case if the machine condition can be monitored continuously to detect the trend of any fault and extrapolate this it is likely to highlight the point of failure in order to pre-plan the necessary maintenance. CM is particularly useful if several systems of the same type are present, as measurements can be cross-referenced to compare the condition of the machine predicted by each. A CM programme may consist of several condition measurement techniques which must all be applied in the correct manner to be able to detect the possible fault indications.

The remainder of this chapter will focus on the different techniques used for diesel engine CM. These topics will be discussed in a general manner because the techniques described are widely applied in all fields of engineering. After this general introduction, the specific subject of the vibration techniques for diesel engine CM is discussed more deeply in Chapter Four.

3.2 Diesel Engine Condition Monitoring Techniques

Today, engine operation, characteristic performance, economy and emission are very important and engine CM is being used to ensure that these characteristics meet required standards. The conventional attitude to engine upkeep has been to follow a fixed routine maintenance program based on the engine manufacturer's instructions. The maintenance schedule is based predominantly on past experience of similar engines. There is no guarantee that an individual component would remain in working condition throughout this interval. On the other hand, the component may still be in a healthy condition even after the elapsed interval and it would be a waste of time and money to repair or replace it. Many techniques are being used for machine CM; this section explains the use of some of these techniques for fault detection and diagnosis in diesel engines.

3.2.1 Diesel Engine CM Based on Pressure Measurements

In a diesel engine fuel injection and combustion are the most important processes. These processes control not only engine performance, economy and emission characteristics but also engine durability. The important parameters of the fuel injection system are injection pressure, injection time, injection rate and injection duration. These parameters determine the effectiveness of the fuel injection process [102] [103].

The in-cylinder parameters that measure the effectiveness of the combustion process include peak pressure, ignition delay, combustion duration, heat release and cumulative heat release rate [104] [105]. The fuel injection pressure and in-cylinder pressure is discussed below.

3.2.1.1 Engine Fuel Injections Based Pressure Measurement

The fuel injection systems of diesel engines require high operating pressures to inject fuel into the combustion chamber and the mechanical design of the fuel injection system is complex. Fuel injection pressure plays an important part in determining the fuel's combustion characteristics and engine power performance. With modern diesel engines with direct fuel injection, the injection pressures generated by the fuel injection pump can range from about 100 bar to about 2000 bar [106], [107, 108]. The fuel injection system must be able to meter the desired amount of fuel, depending on engine parameters such as speed and load: that is, it must inject the correct amount of fuel at the correct time and at the required rate.

Until now researchers have worked on improving fuel injection under different engine conditions to extend working life [109], that the fuel injection system develops more faults than any other part of the diesel engine because the fuel injection pump must generate the very high pressure required for fuel injection which is then transmitted through the injection pipes to the injector. The measured fuel injection pressure can be used to monitor the condition of the fuel injection equipment (fuel injection pump and fuel injector) as shown in Figure 3-1. Monitoring of the fuel injection pump and injector by pressure measurement is usually done by installing pressure sensors in the fuel injection pipe close to the pump and injector; see Chapter 6 for more information. From the pressure measurements, the injection time, injection duration and peak pressure can be found. However, it is difficult to use fuel injection pressure methods to diagnose fuel injection system faults because it is only suitable for use on individual cylinders of an engine, is intrusive and influences performance.

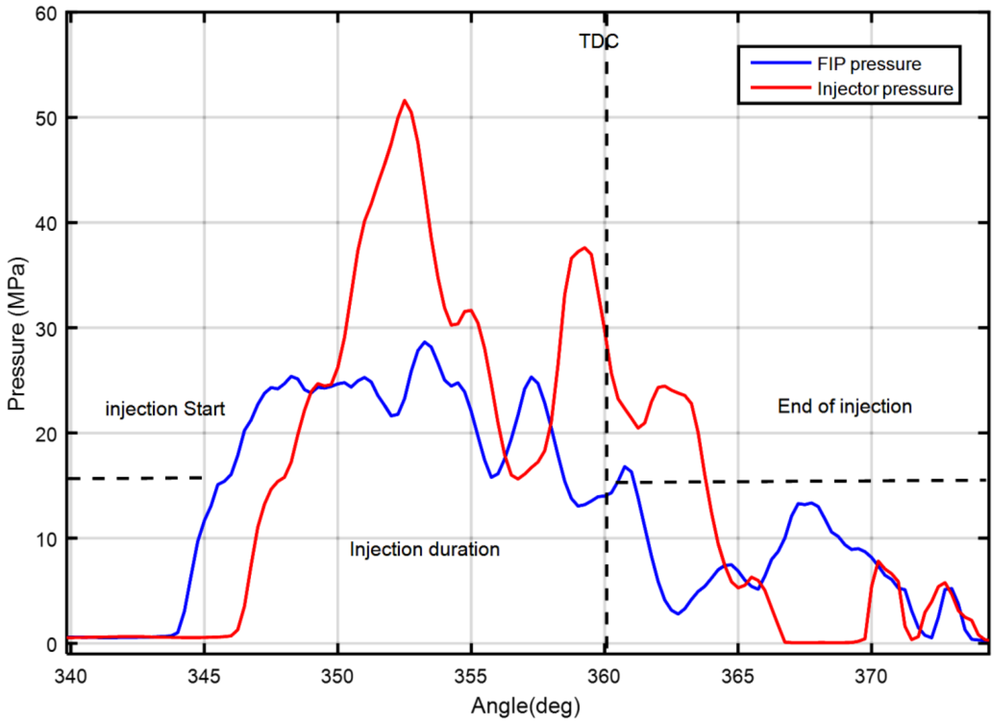


Figure 3-1 Engine fuel injection pressure waveform of fuel injection pump and fuel injector

3.2.1.2 Engine Combustion Process Monitoring Using In-cylinder Pressure

The in-cylinder pressure profile can be considered to be the pulse of an engine and is the parameter most commonly used to study the combustion process. It is well known that cylinder pressure is related to crank angle, for four stroke diesel engines and has been used to obtain quantitative information about the combustion process. In addition, the pressure history inside the engine cylinder gives an indication of the timing and quality of the combustion. The in-cylinder pressure signal provides vital information on peak pressure, P-V diagram, indicated mean effective pressure, combustion duration, ignition delay, heat release rate, cumulative heat release and so on [110].

Many papers have been published to demonstrate the potential of the in-cylinder pressure measurement as a valuable source of information for the development and calibration stages of a diesel engine and that knowledge of the pressure and crank angle at which peak pressure occurs could be part of a powerful diagnostic technique. These measurements can be a direct indication of combustion performance and used to estimate air to fuel ratio and estimate of ignition timing in engines is seen from Figure 3-2. Such measurements should also to be able to detect anomalies such as misfire or poor combustion in the cylinder [111], [112].

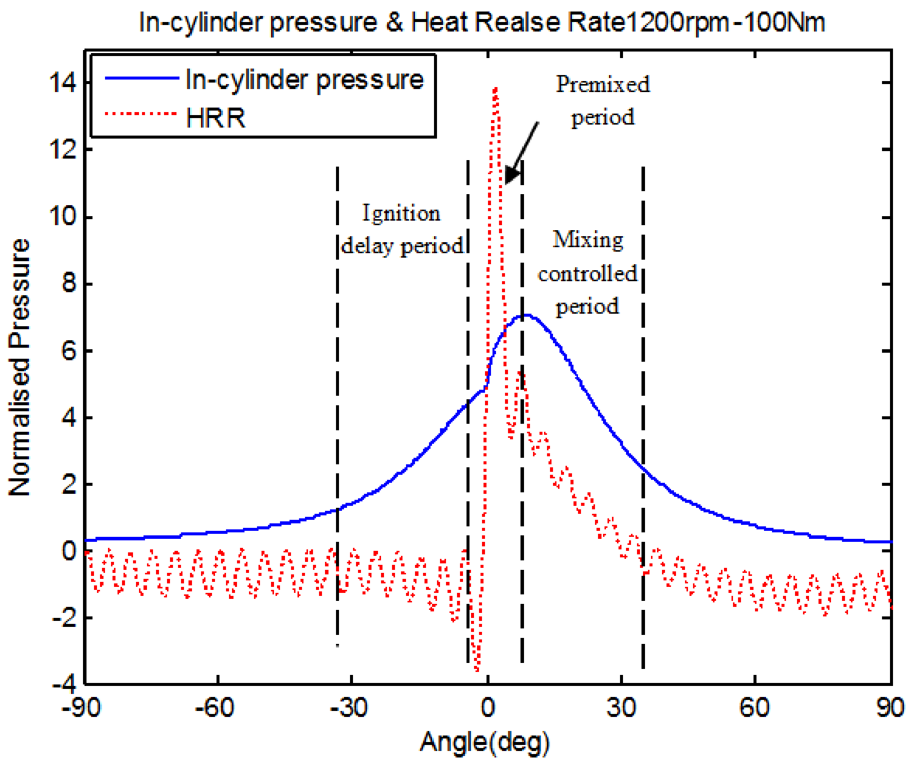


Figure 3-2 Engine combustion stage (in-cylinder pressure with heat release rate)

The heat release rate (HHR) is an extremely important quantity in terms of engine efficiency. Several measurement techniques are available for direct in-cylinder pressure measurement but are not suitable for use with in-service engines because of expense, unreliability, insufficiently robust, not easy to maintain or difficult to calibrate. In-cylinder pressure direct measurement techniques are not suitable for monitoring just one engine cylinder. The major drawback of the in-cylinder pressure as a method for the CM of fuel injection and internal combustion of diesel engines is that it is intrusive and affects engine performance.

3.2.2 Diesel Engine Based on Instantaneous Angular Speed

Flywheel instantaneous angular speed (IAS) of a diesel engine contains significant information about in-cylinder pressure and has been used to detect faults within the combustion process. This technique is based on the fact that, even when the engine is running smoothly at a constant rpm, the IAS of the flywheel undergoes cyclic variations, increasing as the cylinder fires and decreasing with subsequent cylinder compression [113].

Applications of this method tend to use encoders fitted to the crankshaft of the flywheel. Cylinder to cylinder variations are identified from frequency domain harmonics, with the dominant harmonic at the cylinder firing rate and sub-harmonics indicating differences between cylinders. Many of the frequencies detected in practice are not directly related to cylinder firing but have been shown to be caused by engine accessories. **Figure 3-3** shows the IAS waveform for a four stroke diesel engine. This method has been shown to have a high diagnostic success rate [114].

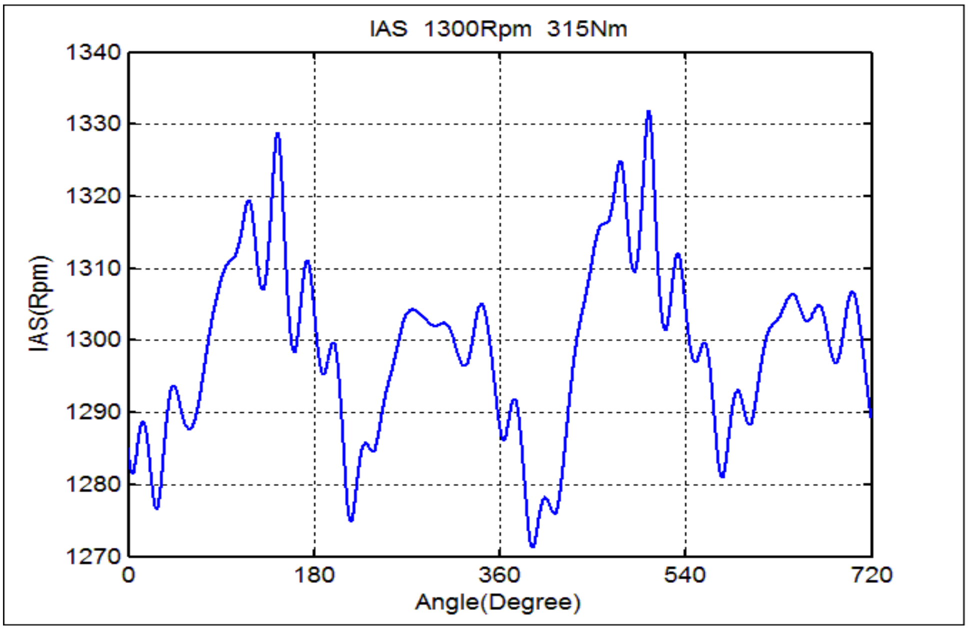


Figure 3-3 Engine combustion process at one cycle

While the IAS method has been shown to be very capable in detecting engine misfiring, and useful for confirming the identification of faults detected by other methods, to date IAS is not generally able to diagnose faults. With advances in on-board computational technology this method has been able to locate faults to a particular cylinder but cannot diagnose the faults [115].

3.2.3 Diesel Engine Based on Air-borne Acoustic Method

Air-borne acoustic analysis is not nearly so widely used as vibration monitoring for the CM of diesel engines, due to the greater complexity of analysis of multiple sound signals from complex rotating machinery for successful fault diagnosis [116]. For diesel engines, the principal relationship between the rise of combustion pressure and the noise produced by the engine was described by Ricardo as long ago as 1931 [117].

An engine has a large number of acoustics sources, all of which can - generally - be divided into two categories: airborne or structure borne [118]. Air-borne sound received at the microphone will have been generated by many different systems and mechanisms (e.g. exhaust) and travelled via a number of transmission paths. Structure borne sound refers to that noise generated by vibrations induced in the structure itself that excite the engine surfaces and cause them to sound noise. The radiated noise levels from diesel engines can be affected by a variety of factors such as engine type, structural specifications and operating conditions [119]. Previous work has provided noise level prediction criteria and design fundamentals, but most are based on specific diesel engines [120]. As a result, their effectiveness in predicting radiated noise levels for other engines is very limited due to the vast differences between specifications and working principles of different engines.

Figure 3-4shows a microphone signal representing the airborne noise waveform of one cycle of a four stroke diesel engine.

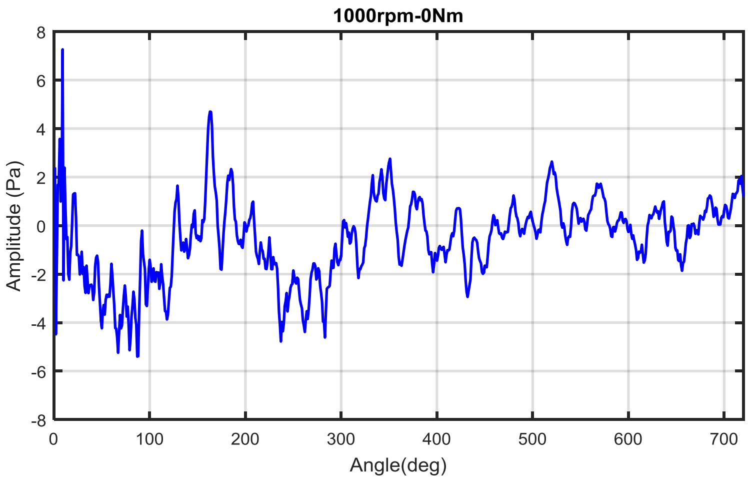


Figure 3-4 Airborne acoustic (Sound) of Engine for one full cycle of a four stroke diesel engine

The combustion noise is a highly complex phenomenon, the level and sound quality of which is generated by turbulent fuel combustion. It occurs towards the end of the compression stroke and subsequent expansion stroke. The rapid pressure changes within the combustion chamber due to the combustion process result in vibrations being transmitted through the engine's structure, contributing to the engine noise levels both as airborne and structure borne noise [121]. The pressure variation in the engine cylinder plays an important role in determining engine performance. Thus analysis of the combustion noise and sound quality characteristics of any fuel should be useful as a diagnostic tool. The drawback is that the combustion noise is generated in an already noisy environment.

3.2.4 Diesel Engine CM Based on Acoustic Emission

Acoustic emission (AE) is widely applied to, amongst other things, especially in pipeline testing evaluation of ageing aircraft, rocket motor testing, transformer testing, inspections of valves, production quality control, in steam lines, wind turbine monitoring earthquake prediction and ship hull monitoring. AE has also demonstrated a real time capability for the early and rapid detection of defects, faults and cracks, with a resulting minimisation of plant downtime for inspection.

AE measurement techniques involve the detection of stress waves; usually within a range of 100 kHz to 1 MHz [122]. This is a relatively high frequency range and so places the signals to be detected outside the range of likely structural resonances and mechanical background noises to be found in diesel engines, giving it a much higher signal to noise ratio than is normally attained with vibration or sound measurements. Thus, CM using AE can be very effective in real industrial settings.

However, because of the high frequency of the AE signals they are damped very rapidly with distance from source. This has the advantage that the AE signals are unlikely to be influenced by sources some distance away, but the disadvantage that the sensor should be close to the source, and the closer the better [123]. This means that AE signal is far more localized, that's, appearing virtually only from the source where they are generated.

Moreover, differential damping of different sources is crucial in sensor a location consideration which is due to material interfaces along the signal path. That's necessary to ensure good signal continuity from the surface to the sensor and high vacuum grease is often used as a coupling [124].

3.2.5 Vibration Condition Monitoring

All the rotational machines contain many moving components that give rise to vibration and noise. Any change in the condition of the machine is indicated by a corresponding change in vibration response. The vibration signal can be used for CM and to detect defects before they reach a critical condition. The vibration signal can be monitored and used not only to detect the presence of a fault but also to diagnose that fault, assess its level of severity and predict time to failure giving time to make arrangements for its correction, minimising disruption of, say, a production process.

Monitoring and analysis of measured vibration signals are widely used for determining the condition of a mechanical machine or dynamic system under different operating conditions. The vibration response can offer early detection and diagnosis of problems giving the operator time to make crucial decisions on maintenance before any serious problem or unscheduled downtime occurs. State of the art CM and fault detection and diagnosis techniques using vibration measurement have been applied with great accuracy to fuel injection system components and engine combustion process and these are discussed on next Chapter.

3.3 Summary

This chapter has reviewed the literature concerning the CM of diesel engines using different methods. The review included such commonly used parameters as in-cylinder pressure and fuel injection pressure, airborne acoustics, IAS, and vibration methods. This chapter has given a general view to help in developing CM techniques for diesel engines; the next chapter will present vibration method diagnosis fuel injection system and engine combustion process.

CHAPTER FOUR

4 VIBRATION ANALYSIS BASED ENGINE DIAGNOSTICS

This chapter describes the diagnostics of diesel engines based on measured vibrations. The vibration responses of the fuel injection system and internal combustion process of a diesel engine are reviewed. The likely principal faults occurring within the fuel injection system and combustion process are presented and relevant vibration measurements and analysis procedures for diagnostics and condition monitoring are discussed show its merits and shortages. In addition, more understanding of vibration is also paid to engines running with biodiesel.

4.1 Vibration Monitoring as a Diagnostics Tool

Typically, the amplitude of the vibration response can provide an early indication of the severity of a problem and analysis of the frequency content of the signal can indicate the source of the defect [125]. The extraction of these measures can provide a valuable diagnostic tool to predict run-up to failure of machine components. It is a very challenging task to extract useful feature from the acquired signal, due to the likely interference of high levels of noise. Thus, there is a need to develop a high level processing and analysis system to extract useful information from the measured data about the health of the machine.

The review in this chapter focuses on monitoring the fuel injection system and combustion process of the diesel engine using the measured vibration response. High pressure fuel injection is a complex and sensitive process with a relatively high rate of failure. The idea here is to use its vibration response to monitor the fuel injection process and detect and diagnose faults in engine valve train affected to fuel injection. The vibration of the fuel injection system is caused mainly by the pulsed forces generated by the fuel delivery valve and injector needle valve. Reviews of the sources of vibration in the fuel injection system and engine combustion are provided later in this chapter.

4.2 CM of Diesel Engines Using Vibration Measurements

There are many different excitation sources of vibration in the fuel injection and internal combustion processes of diesel engines, especially in four-stroke engines [126]. Figure 4-1 shows a schematic of the basic terms, sources and paths of noise and vibration transmission in an engine in a manner convenient for this research. The model is helpful in considering and analysing vibration mechanical sources. The following sections discuss vibration generation in fuel injection pumps and by internal combustion in diesel engines. Diesel engine vibration sources are reviewed and how time domain and frequency domain methods can be applied to engine body vibration measurements to extract useful information for determining the health and performance of the diesel engine under different speeds and loads [127, 128].

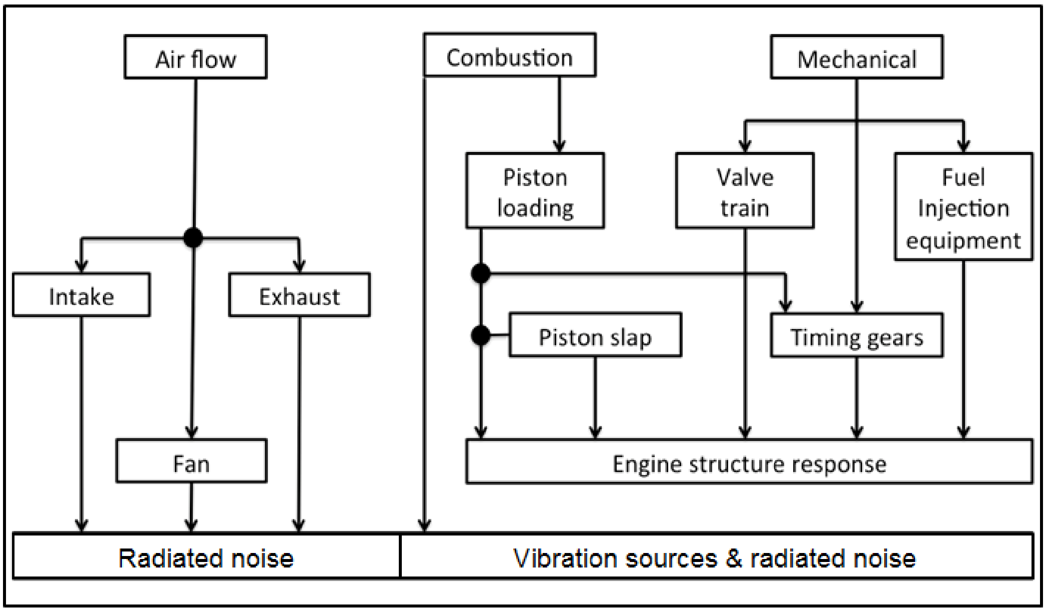


Figure 4-1 Diesel engine: noise and vibration generating sources [27]

4.2.1 Fuel Injection Monitoring based on Vibrations

A high pressure fuel injection system includes the fuel injection pump, a fuel injection pipe and a fuel injector. As see Figure 4-2, and is considered a core element of any diesel engine and, (as discussed in Chapter One), contribute the highest percentage diesel engine faults. The main source of vibration of the fuel injection system is the high pressure necessary for the proper functioning of the fuel injection pump and fuel injector [13], [108], [129, 130], [131] and [132]. These high pressures generate large forces within the fuel injection pump, fuel delivery valve and fuel injector needle. So it is important to monitor the fuel injection system vibration to ensure it remains within acceptable limits. Using signal processing and analysis, important parameters such as the fuel injection advance angle can be extracted and used to identify the state of the fuel injection. In a word, a new non-destructive method is presented to measure and monitoring fuel behaviour on fuel injection and used for fault detection and diagnosis.

However, in this research, the high pressure equipment (fuel injection pump and fuel injector) are studied to better understand the mechanical sources of vibration and monitor fuel quality in greater depth in the following the sections

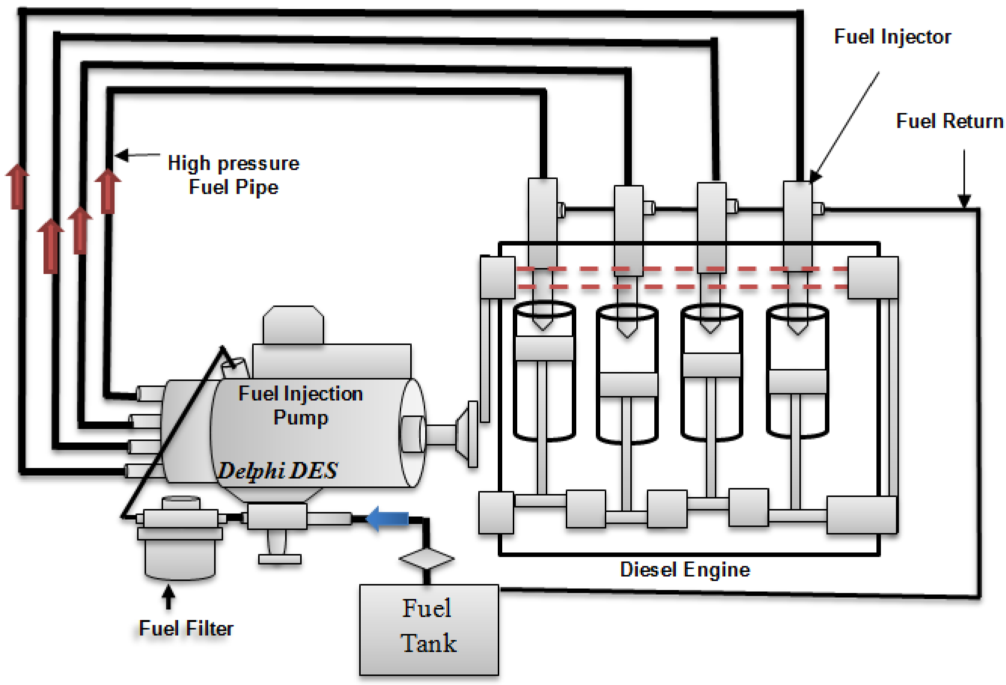


Figure 4-2 Schematic of fuel injection system of diesel engine

4.2.1.1 Fuel Injection Pump Vibration

The rotary distributor fuel injection pump (FIP) for diesel fuel used in this research has a single plunger and barrel, where the plunger combines rotary and reciprocating movements by rotating the cam plate as shown in Figure 4-3. To achieve the required fuel injection, the pump must raise the pressure of the fuel sufficiently (several hundred bars) to rapidly open the delivery valve in micro-seconds. This allows the fuel to be forced into the injector nozzle at the correct time for each engine cylinder [54, 133] [134].

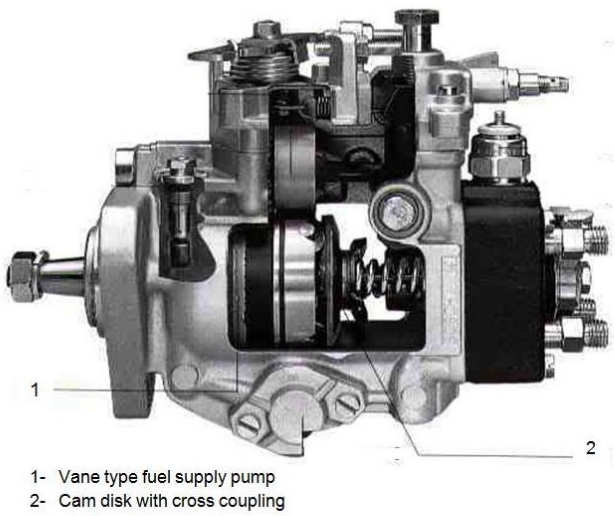


Figure 4-3 A rotary distributor fuel injection pump [135]

The rotary and reciprocating movements of the fuel pump will be accompanied by internal dynamic forces including that of fuel pressure in the barrel, the forces between the cam and roller and also the recovery forces due to the spring. These forces will cause pump components and body to vibrate and, possibly, the repetition rate may cause component resonance. The impact of the delivery valve on the valve seat will cause the pump body to vibrate. These vibrations become stronger at higher engine speeds and loads because of a higher rate of fuel delivery and could mean the character of the vibrations will change with different types of fuel and delivery rates [17, 136],[137].

These effects are demonstrated by the vibration and injection pressure measurements made at fuel injection pump, see Figure 4-4. The vibration peaks relate to the opening and closing of the valves at the start and end of the high pressure pulse. This is discussed further in Chapters five and seven, and includes the effects of forces due to fuel injection pressure on the delivery and injector needle valves.

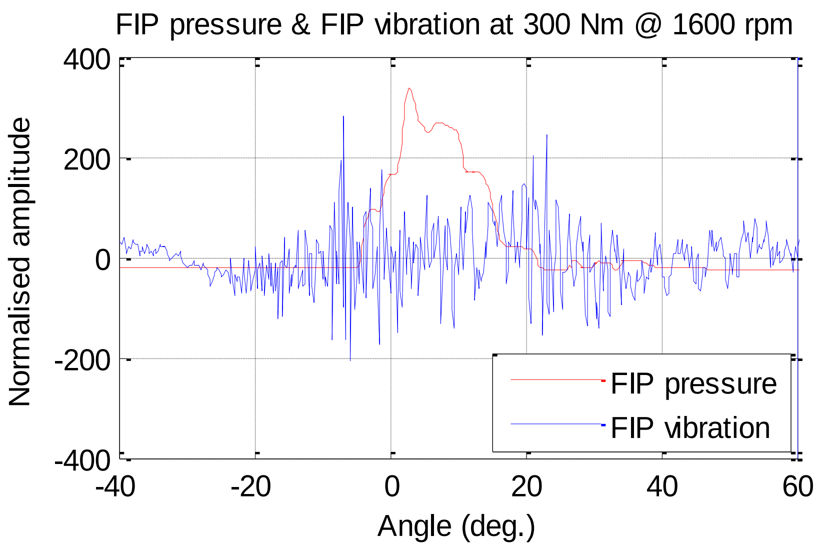


Figure 4-4 Fuel injection pump vibration and pressure measurement with crank angle

4.2.1.2 Fuel Injector Vibration

The main role of the fuel injector in a diesel engine is to spray fuel into the combustion chamber at the required rate, at the appropriate time and for the necessary duration. The needle of the injector valve opens under high pressure and fuel is sprayed from holes in the injector into the combustion chamber, the drop in pressure allows the needle valve to return to its initial position under the action of the spring. The mechanical impact of the fuel injector needle is called an injector tick [138].

The initial build-up of pressure in the injector which forces fuel through the injector holes is associated with a small impact between the needle and valve seat before the needle is fully open. The needle lifts and fluid flows through injector nozzle, there is a second impact as the needle hits the backstop. With the release of pressure, the fuel flow is reduced, the force of the spring closes the needle and there is an impact between the needle and its seat. Finally, after the needle has closed, there are back pressure fluctuations in the fuel line (repeated pressure reflections between needle and plunger of the fuel injection pump in the fuel delivery line) [123].

4.2.2 CM of Engine Combustion Characterisation Using Vibration Responses

The sources of vibration in diesel engines have been attributed to the combustion process, piston slap, fuel injection and valve operation, [127, 139, 140]. Few researchers have attempted to explain how diesel engine vibrations are related to fuel ignition or explosion of the fuel-air mixture at high temperature in the complex geometry of the combustion chamber.

The engine vibration signals were related to the combustion process as shown Figure 4-5. It can be seen that higher cylinder pressures and faster pressure changes resulted in higher engine vibration levels. The variation of engine vibration is related to changes in the in-cylinder pressure. When the combustion begins in the cylinder, the cylinder pressure increases very quickly and generates the vibration of the engine [141, 142]. However, as can be seen from Figure 4.4 the vibration signal is very noisy after the peak pressure and may not be capable of effectively determining the combustion timing. Thus, the vibration signal may be limited to accurately detecting the change in cylinder pressure corresponding to the start of ignition before the peak pressure occurs [142].

Nevertheless, in this research the vibration response has been successfully used to study the combustion process in four stroke diesel engines under different operating and fuel conditions.

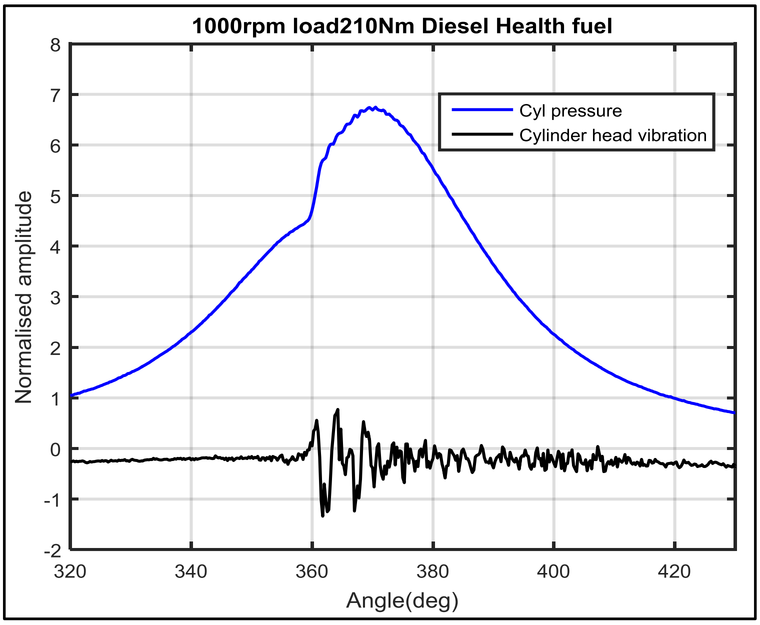


Figure 4-5 Engine vibration and in-cylinder pressure as a function of crank angle

4.2.3 Condition Monitoring for Diesel Engine Running with Biodiesel Based on Vibration

The combustion process of diesel engines is usually represented by the in-cylinder pressure signal and it has been found that the combustion profile using biodiesel is similar to that obtained for petro-diesel [18]. Many researchers have investigated the effects of biodiesel on diesel engines using cylinder head vibration measurements. Taghizadeh-Alisaraei, et al., [143] investigated engine vibration of a Perkins six-cylinder diesel engine running on different blends of biodiesel. The vibration signals were analysed using time-frequency domain analysis. It was found that fuel blend significantly influenced vibration levels, but not in a consistent manner. It was demonstrated that, B20 and B40 had the lowest levels but B15 and B30 had the highest. Taghizadeh-Alisaraei, et al., [144] extended their investigation to include engine knock. Now it was found that the maximum vibration signal was obtained for the B20 and B40 blends and the minimum for the D100 and B80 blends. In these circumstances the B40 blend also had the lowest power, the losses occurring due to the uncontrolled vibrations. The power was almost the same for the other fuel blends.

Moreover, Wongchai et al., [145] and B. Heidary, et al., [146] obtained similar results when investigating vibration of a engine fuelled by biodiesels and petro-diesel. Using the time-domain average peak acceleration it was found that engine vibration was a minimum for B100, B20, B5, and highest for B15 and B10. These researchers also found, as would be expected, that vibration levels were significantly affected by engine speed.

Abdolahzadeh, et al.,[147] investigated engine vibration with low percentage biodiesel (B0, B2, B4, B6 and B8). There was a general decrease in RMS vibration level with an increase in biodiesel, but with the exception of a sudden and significant increase at B4. Manieniyan, et al., [148] investigated engine vibration using B100 biodiesel for two different positions of the vibration sensor. It was found that the acceleration vibration is higher for the biodiesel at the cylinder head position, but lower at the bottom of the crank case. The maximum vibration amplitude was found to be related to the rate of pressure rise and the maximum pressure in the cylinder during ignition. When the rate of pressure rise increased so did the vibration amplitude.

How, et al., [149] also investigated engine vibration level and cylinder pressure rise for D100, B10, B20, B30 and B50. It was found that RMS acceleration was affected by biodiesel fuel blend. The vibration level decreased consistently with increase in biodiesel with B50 producing the lowest acceleration levels, 13.7% below that for D100. Harun et al., [150] used RMS vibration to analyse biodiesel blends fuelling a diesel engine. The results showed highest levels of engine vibration was achieved with B20 with compared to petro-diesel at a load of 100 Nm. Ravi, et al., [151] investigated vibration and noise of a diesel engine fuelled with biodiesel. The noise and vibration of the engine is reduced when operating on biodiesel, but with biogas (B20 mode) the noise and vibration increased slightly because of air knocking effects of the biogas. Up to a 20% volume the biodiesel does not affect the performance of the engine, but B20 engine vibration is increased slightly. Moreover, significantly the engine parameters affect the engine vibration [152].

Previous research has demonstrated that engine performance and vibration levels can differ significantly between petro-diesel and biodiesel blends. This research further investigates these different effects of the fuels.

4.2.4 Engine Valve Train Fault Detection and Diagnosis Using Vibration CM

In a four-stroke diesel engine, there are many vibration sources such as engine valve impacts, piston slap and injector tick. These sources are all short lived in duration and occur at fixed points regarding the angular position of the crankshaft. The combustion noise and vibration happens once around the top dead centre (TDC) at 0^0 and then every 720^0 turned by the crank. Gear timing is an important principal of operation of internal combustion engines. The operation of the valves of a four-stroke diesel engine is shown in Figure 4-6, the inlet valves and exhaust valves fire in the order 1-3-4-2 which is the same as the research test rig

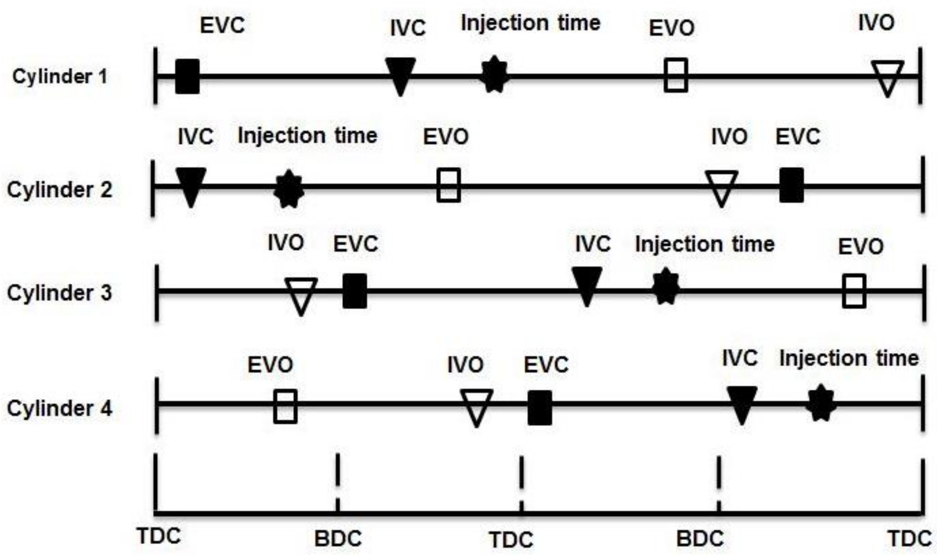


Figure 4-6 Diagrams of engine valves operation such as inlet valve and exhaust valve with injection time

It is especially important to maintain valves in a good condition for as long as possible, with an acceptable level of tightness during periods of closure. Insufficient tightness of the inlet valves causes a reduction of engine power and an increase of specific fuel consumption. Leaky exhaust valves affect engine power to a lesser degree, but leakage here causes a rapid increase in wear as a result of combustion gas blow-by, which often leads to damage of the entire cylinder head [153]. This can reduce the effectiveness of any catalytic exhaust and even its complete destruction. The symptoms of valve burn-out in its first stage can be effectively counter-acted by adaptive systems of control of the engine combustion [154, 155].

However, with four-stroke IC-engines, as the valve clearance becomes greater, the closing time advances and the closing velocity and acceleration increases [156], This leads to an increased impact force upon the valve seat and cylinder head. In contrast, this impact force upon the valve set decreases if the valve clearance becomes smaller [157, 158]. Time domain features extracted from vibration signals measured on a diesel engine were successfully used to classify an intake valve clearance fault when Ftoutou, et al., [158] identified engine intake valve clearance faults by applying neural networks to the time domain signal.

Nevertheless, from a review of previous work, it is clear that faults with valve clearance is important for the efficient operation of diesel engines and will become even more important when using different fuels which require increased pressure inside the combustion chamber. In such a situation there will be greater forces on the valves train of the diesel engine. This research investigates the identification of faults in the clearance of internal combustion valves based on fuel injection vibration response.

4.3 Signal Analysis Techniques for Vibration Responses

The main goal of the analysis of the vibration signals is to determine the magnitude of the vibration related to the movement of a specific component. Success in vibration analysis depends on the data acquisition system and subsequent data analysis. At its simplest level has determining the trend of the overall vibration amplitude level. The next stage is measuring the amplitude and frequency of the individual component vibrations and their related phases, then more sophisticated and higher level analysis techniques are applied such as wavelet analysis [159].

Machine vibration monitoring techniques are usually based on the time, frequency and time-frequency domains analyses. Time domain and frequency domain techniques start with the signal waveform in the time domain, a transform and statistical analyses. There are a large number of signal processing techniques that can be used to extract information of interest from a measured vibration signal concerning defects. The major challenge for CM is to find the most suitable for each specific task. As a matter of fact, the type of signal to be analysed has an influence on the type of analysis to be carried out and also on the choice of analysis parameters. Thus, it is important to examine the various types of signal parameters that are encountered in practice. The basics of these parameters are outlined below.

4.3.1 Time Domain Analysis of Vibration Signal

Vibration waveforms, even non-stationary signals, can be presented as a function of time which is a graph of the amplitude of the vibration signal. The raw data is obtained from the vibration sensor. The statistical method is widely used to determine useful characteristics from apparently random vibration signal characteristics of a dynamic system. Statistics are able to summarise the vibration data obtained and to draw meaningful and useful conclusions. The most important and common of the statistical time domain parameters are the root mean square amplitude (RMS), crest factor (CF), peak value (P), skewness (SK) and kurtosis (KT) [160, 161].

The peak value (X_P) is the maximum absolute value of the waveform signal. In a set of data X1, X2…X n, P is being explain as [160, 161]:

$$X_P = max(|X|) \quad 4\text{-}1$$

Where, X_i is the i^{th} value of variable X, n is the data number points and $|X|$ the absolute value of X.

The root mean square (RMS) value of the amplitude is a measure of the amount of energy contained in the signal. The RMS of variable X is the square root of the arithmetic mean of the sum of squares of the X value. . In a set of data $X_1, X_2 \ldots X_n$; X_{RMS} is defined as [160, 161].

$$X_{RMS} = \sqrt{\frac{\sum_{i=1}^{n} X_i^2}{n}} \quad 4\text{-}2$$

The crest factor (CF) can be a measure of the sharpness and number of the peaks in the signal waveform which can be used to determine whether a signal contains repeated impulses. A high value of CF on a signal vibration can be indication of machine condition. The CF is the ratio of the peak value (X_P) to the RMS value (X_{RMS}) of a waveform signal [160, 161].

$$CF = \frac{X_{PK}}{X_{RMS}} \quad 4\text{-}3$$

The Kurtosis (KT) is a measure the distribution of the data is peaked or relatively flat. It is compared with the Gaussian or Normal distribution, for which the kurtosis is equal to 3. Also the data X1, X2…Xn, the formula for kurtosis (relative to normal) is explain by equation (4-4) [161].

$$KT = \frac{\sum_{I=1}^{n} (X_i - \overline{X})^4}{(n-1)S^4} - 3 \quad 4\text{-}4$$

Where $\overline{X}$ is the arithmetic mean of the data set and S is the standard deviation of the distribution, expressed by equation (4-5) [161]:

$$S = \sqrt{\frac{\sum_{i=1}^{n} (X_i - \overline{X})^2}{n}} \quad 4\text{-}5$$

If KT is negative then the distribution is flatter than the Gaussian, and if KT is positive it means the distribution is more peaked than the Gaussian.

4.3.2 Frequency Domain Analysis of Vibration Response

Frequency domain signal analysis is the most commonly method used for analysing a data of vibration response. The frequency domain analysis is most basic type of Fast Fourier Transform (FFT), which can convert a signal from the time domain into the frequency domain which as function in frequency. Frequency domain or spectrum analysis is the result of taking the Fourier transform of such a dB power spectrum; it is the spectrum of the logarithmic power spectrum. If the power spectrums $S_X(\omega)$ of the time signal x (t) is expressed as:

$$S_X(\omega) = |F\{x(t)\}|^2 \qquad 4\text{-}6$$

then the power spectrum, $Cp_X(\tau)$, is a real valued function and is the inverse of the Fourier transform of the square of the logarithm of the power spectrum of the signal (Norton & Karczub, 2003):

$$Cp_X(\tau) = F^{-1}\{log_{10} S_X(\omega)\}^2 \qquad 4\text{-}7$$

Power spectrum signal analysis is a complementary tool to identify components Trending analysis is used to predict the probability of occurrence of future events, the RMS value of vibration signal on the time domain is examined and plotted over time and if the amplitude exceeds a certain critical level, and then remedial action is taken. However, the vibration response of an engine, while generated by the individual parts, also that’s will be affected by their assembly, interaction and installation. By comparison of the actual frequency domain amplitude with a signal from a healthy condition engine, the status condition (satisfactory, good, and unacceptable) may be determined.

4.3.2.1 Frequency Domain Analysis of Fuel Injection Vibration Response

Frequency domain analysis of the vibration signal is used for more complex machinery such as gearboxes, turbines, compressors, diesel engines and reciprocating machines because these will generally require more sophisticated analysis, at least to realise the full diagnostic power which vibration monitoring offers [162-164]. Tomaszewski and Szymański have presented a new and interesting approach to vibration diagnostics of the internal combustion engine selecting test points on the basis of impact tests. They analysed the measured vibration signals and were able to relate measured values to the internal combustion valves faults [164].

The benefits to be gained from frequency analysis techniques are greater advanced knowledge of impending failure and a better indication of what that failure might be. This is particularly valuable for critical machines in the continuous process industries. Moreover, it is possible to generate an approximation to an impulse which has a fairly flat spectrum over the desired frequency range of interest [165]. In this research, frequency domain techniques are used to monitor, detect and diagnose possible fuel injection faults in a IC diesel engine. The fuel injection pump vibration excitation mechanisms to be investigated are shown in Figure 4-7. It is expected that the vibrations due to high-pressure forces in the fuel delivery system, injector and valves will be relatively high frequency and the vibrations induced by the contact forces between cam and roller, which are lubricated, will be relatively lower frequency.

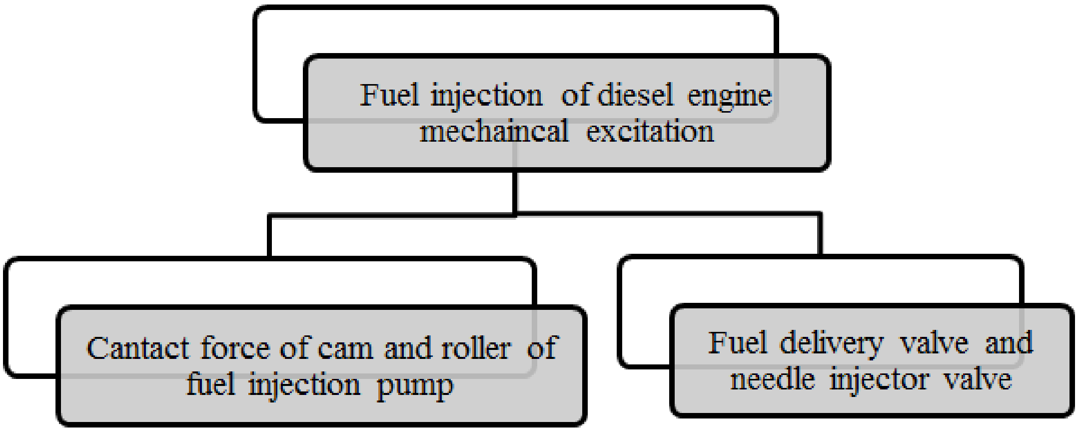


Figure 4-7 Schematic of fuel injection mechanical excitation of diesel engine

Howver, the high frequency envelop have been used on fuel injection pump vibration resopnce. This method analysis gives good results particularly on dignostic and detection engine valves train condition.

Envelope techiques analysis can be used for monitoring and diagnostics to investigation of diesel engine condition. In this resurech the envelope analysis is an excellent tool for detection of engine faults condition and rotray machinry[166].

4.4 Summary

This chapter has reviewed the literature regarding fuel injection and combustion induced vibration in diesel engines, and presented a viable CM method based on surface vibration measurements for fault detection and diagnosis.

Also in this chapter has given a view to help in developing CM techniques for diesel engines for vibration method analysis, angler domain, RMS value, frequency range and high frequency envelop amplitude. These mothers used to monitor and diagnosis fuel injection system and engine combustion process condition in this research.

CHAPTER FIVE

5 DYNAMIC MODELS OF FUEL INJECTION SYSTEMS AND NUMERICAL STUDIES OF BIODIESL INJECTIONS

This chapter develops a dynamic model for the fuel injection system in a diesel engine. This model allows simulation studies of the impact responses at the delivery valve and injector needle valve under different fuel properties. In addition, flow characteristics are also investigated to correspond to the impacts and dynamic loads applied to the fuel equipment through a symmetric numerical study of different fuel deliveries.

5.1 Introduction

The mathematical analysis of the pressure forces that generate significant mechanical impacts in fuel injection systems during engine operation is very complex. The contributions of physical fuel properties such as fuel density, viscosity and bulk modules on fuel injection pressure at the fuel delivery valve and needle injector valve may enhance unwanted oscillations in the system. Such effects may also affect unwanted emissions from the engine which may be exacerbated. Nevertheless, the vibration responses to the impacts can be used to diagnose these changes for verifying the model and implementing online monitoring.

Many researchers have investigated the dynamic fuel injection pressure waveform of fuel injection systems of diesel engines. In 1971 Wylie et al., [167] presented an analytical simulation of the fuel injection phenomena for each part of the fuel injection system of a diesel engine and found reasonable agreement with experimental results. In 1987 Sobel presented a hydro-mechanical model of direct and indirect fuel injection systems, including the fuel injection pump and fuel injector. The model simulation demonstrated that the pressure injector needle is at a higher pressure then the fuel delivery valve of the fuel injection pump. In 1997 Shin et al, [168] presented a mathematical model of fuel injection pipe pressure and related it to the injection pipe length. They found different pipe lengths affected fuel injection parameters and engine combustion.

In 2004 Gullaksen, [169] investigated the dynamic flow in a fuel injection system using numerical analysis and computer programs written in MATLAB, but without external validation. In 2012 Sabau, [170] carried out a mathematical analysis of the fuel injection system of diesel engine and derived the waveform of the injection pressure. The model was divided into three parts: pump, pipe and injector nozzle. In 2013 Kegl et al. [171], analysed the fuel injection system of a direct injection diesel engine. The model considered the injection pressure at each part of fuel injection system, injection duration, injection time, injection rate and injector needle lift, and also analysed the phenomenon of interaction between injection pressure of the fuel injection pump and injector pressure.

However, few researchers have investigated mathematically the forces generated by the fuel injection pressure on the fuel injection equipment. In 1976 Gu and Ball [172] presented a detailed dynamic model for the motion of the needle in a DI diesel engine. Their model predicted specific impact characteristics for the needle when opening and closing, which were confirmed by experiment. Cao et al., 2014 [173] divided the excitations of the diesel engine fuel injection system into two kinds; mechanical and fluid. The mechanical excitations were found to be, generally, below 500 Hz, and were due to contact forces of the cam with roller and the needle valve impacting with its seat. Lejda, 2005 produced a mathematical model of the in-line injection pump of a diesel engine and found good agreement between predicted and measured pressures in the pipelines before and after the injector pump. In 2015 Marcic et al., [174] presented a mathematical model for the injector of a common rail fuel injection system and modelled pressure phenomena using a computer simulation which allowed the calculation of important parameters such as injector pressure, acceleration and velocity of the needle, and fuel injection rate.

Such a simulation of fuel injection dynamics, if successful, would reduce the time and cost associated development processes. The simulation described here was motivated by the need to address effects that are important at the high pressures present in, e.g., the fuel injection pump, delivery valve and fuel injector and offers the capability of evaluating the effects of differences in fuel properties on design parameters including fuel delivered pre-stroke, fuel injection rate and critical fuel injection pressures. This is important because key physical properties of biodiesel and biodiesel blends, such as density and viscosity are higher than for petro-diesel. The simulation develops a non-linear mathematical model for the pressure dynamics of the fuel injection process for the fuel injection supply: fuel injection pump, fuel delivery valve, and fuel line and fuel injector. The mathematical model was written in MATLAB platform an approach previously used by many researchers [173, 175-179] for dynamic simulations.

5.2 General Concept

Numerical simulation by Ramirez of the pressure pulses generated by the fuel pump plunger and which propagated through the fuel pipe to the nozzle gave good matches with the experimental data [180]. This method should be able to be used successfully to analyse the effects of differences in fuel properties on pressure behaviour on fuel injection.

Basically, in this research, the mechanical high pressure fuel injection system consists of a fuel injection pump, delivery valve, fuel injection pipe and injector as shown in Figure 5-1. With changing the volume, pressure and fuel quantity of pump plunger, delivery valve, fuel injection pipe and injector as shown Figure 5-2. Thus different pressure forces cause impacts during the operation of the fuel injection equipment, these impacts will be investigated for the delivery valve, the needle of the fuel injector and, in particular, when using different biodiesel blends. This will help determine the effects of different biodiesel blends on pressure fluctuations in the system and vibration of fuel injection pump and fuel injector. The assumption of the model developments are as follows:

- The temperatures during the short duration of an injection processes are considered constant.
- The force of gravity will not be taken into account as the height variations in the injection system are small (less than 30mm).
- The elastic deformation in the injection pipe will not be considered due to the high stiffness of the pipe wall.
- No cavitation or no air is mixed or dissolved in the fuel fluid.
- Due to the short length of the control volumes relative to the pipe length, the pressure wave inside the chambers are considered to spread instantly, meaning pressure increases will take place all through the volume simultaneously.

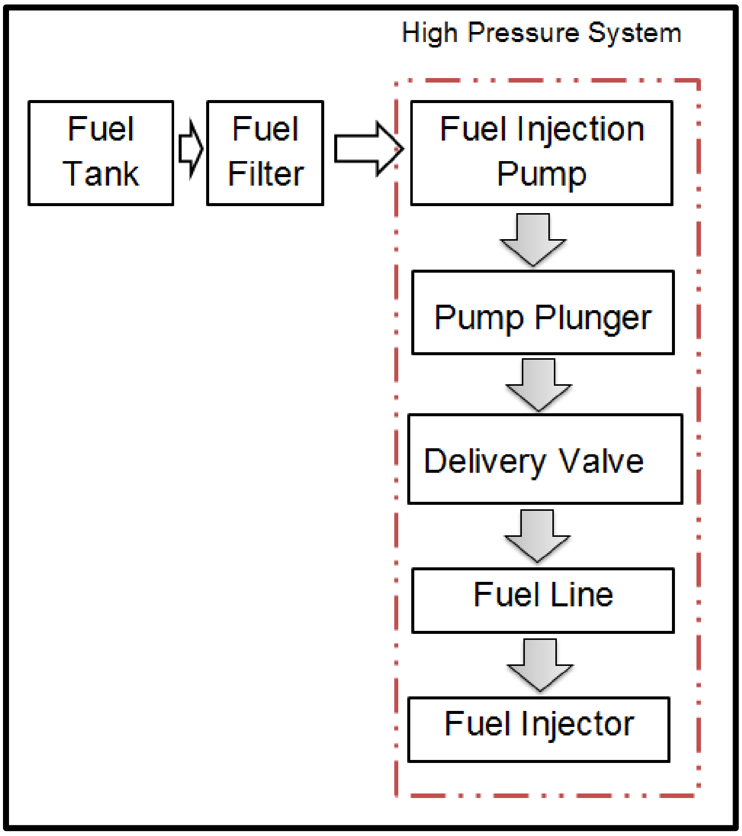


Figure 5-1 Schematic diagrams view of the fuel injection system high pressure

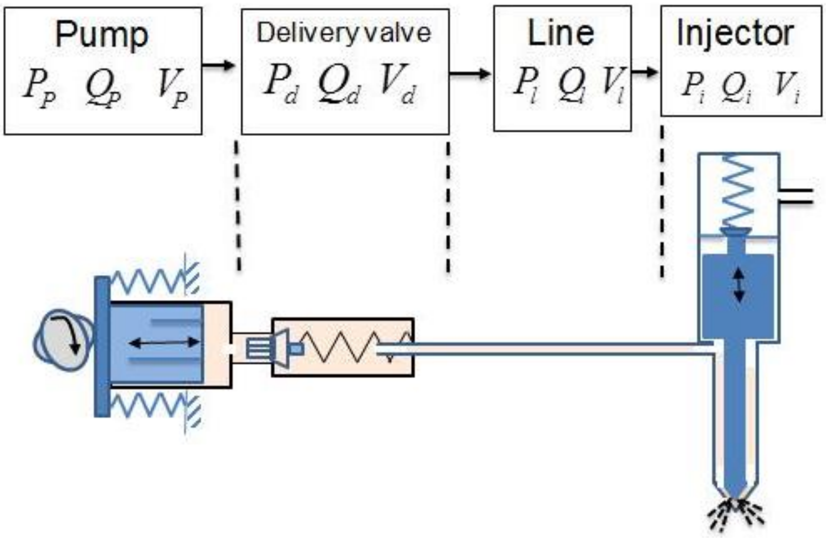


Figure 5-2 Schematic diagrams view of the fuel injection system

5.3 Camshaft Profile

The fuel injection pump camshaft is driven by the engine at half engine speed. The cam actuates the fuel injection plunger which pressurises the fuel. The fuel flow rate delivered by the pump is a function of the rotary speed and angular orientation of the pump plunger. The camshaft profile converts the angular movement of the camshaft into a linear plunger motion by the roller cam follower and plunger return spring. Of course, the individual cam profiles are arranged according to the engine's firing order sequence.

However, the linear velocity of fuel injection pump plunger ($u_{plunger}$) is proportional to the cam angular velocity through the cam profile as:

$$u_{plunger} = u(deg\,Cam)w_{cam} \tag{5-1}$$

Where w_{cam} is the angular velocity of the camshaft and may be in the units of rev/s or deg/sec, and u(deg Cam) is a function which relates the cam lift to the angular position of the cam [169]. The velocity of the cam is assumed constant for the experimental procedure.

5.4 Fuel Injection Pump

The rotary distributor fuel injection pump of the diesel engine used in this research has a single plunger and barrel, where the pump plunger combines rotary and reciprocating movements by rotating the cam plate. To open the delivery valve and achieve satisfactory fuel injection into the combustion chamber, it must raise the pressure of the fuel to several hundred bars in milli-seconds. This section investigates mathematically the movement of the plunger and delivery valve of fuel injection pump.

5.4.1 Model of Fuel Injection Pump Plunger and Delivery Valve

A plunger pump consists of a barrel, plunger, travelling valve and standing valve. The travelling valve is connected to the plunger, so when the plunger moves to passing? fuel to the deliver valve, the travelling valve closes. It is assumed that no fluid flows back through the pump plunger, which forces fluid through delivery valve to the fuel injection pipe. Simultaneously, the standing valve opens and allows fluid to flow into the barrel below the plunger. That's when the plunger reaches its end point and its direction of travel is reversed. The travelling valve opens and the standing valve closes, forcing fluid through the open travelling valve and in front of the plunger. When the plunger reaches its lowest point, it reverses direction passing the fuel to the delivery valve.

The travelling valve closes and the standing valve opens, thus beginning a new cycle. The fuel delivery valve closes off the fuel injection pump high pressure line. That's has the job of relieving the line high pressure by removing a defined fuel completion volume of the fuel delivery phase. That can be ensured precise closing of the fuel injector nozzle which is the injection process end. Simultaneously, stable pressure conditions between injection pulses are created in the high pressure lines, regardless of the rate of fuel being injected at a particular time. The fuel delivery valve opened by the injection pressure and closed by plunger and its return spring. Between the pump plunger's individual delivery strokes for a given engine cylinder, the fuel delivery valve is remains closed. During fuel delivery stage, the high pressure fuel injection generated in pump plunger chamber which is causes the fuel delivery valve to open. Fuel flows deliver with high pressure related to the engine parameters to the high pressure line and the nozzle holder to the injector nozzle open for spring the fuel in engine cylinder [181].

5.4.1.1 Characteristic Plunger Pump Equations

A single plunger fuel injection pump is used exclusively and the plunger is actuated by a cam whose contour exerts considerable control over the injection parameters. The fuel injection pump has a single plunger and barrel assembly to inject fuel into each cylinder. The pump camshaft – an integral part of the pump driven by the engine - forces the pump plunger in the delivery direction. The plunger is returned by its spring. The plunger area, boost stroke and volume are calculated based of the data presented in Table 5-1, and the equations show in appendix of mathematical.

Table 5-1 Plunger of fuel injection pump data

Rotary distributor fuel injection pump	Single plunger
Plunger diameter	7.0 mm (4 off).
Boost stroke	5.9 to 6.1 mm.

The velocity of pump plunger can be obtained using Equation (5-2).

$$v_P = 1/2u_p B_s \pi / u_t \sin(\pi u_m / u_t) \qquad (5\text{-}2)$$

v_P Is velocity of plunger, the pump plunger movement each stroke can be explaining by Equation (5-3)

$$d_p = B_s / 2(1 - \cos(\pi u_p / u_t)) \qquad (5\text{-}3)$$

d_p Is plunger displacement, the fuel flow rate through pump plunger chamber can be expressed as Equation (5-4)

$$Q_P = C_q A_p \sqrt{\frac{2}{\rho}} \, (P_P - P_0) \qquad (5\text{-}4)$$

C_q is discharge coefficient, ρ is fuel density, P_P is the pressure inside plunger chamber, The fuel density due to the variation in plunger chamber pressure can be calculated using Equation (5-5) [182] This will assist in determining the effects of biodiesel and biodiesel blends on fuel injection pressure.

$$\rho = \rho_0 \left(P \; T\right) \qquad (5\text{-}5)$$

, where ρ is fuel density, ρ_0 is the fuel density at the initial pressure, is the local fuel injection pressure, and, and *T* is the fuel temperature,

The plunger contacts the delivery valve collar and fuel travel to rapidly lift the valve off its seat, and the spring reseats the valve when current and magnetic flux drop off. Both plunger and delivery valve are light in weight, the delivery valve is loosely guided in the plunger, and only the valve seat is lapped. However, in the plunger chamber, the pressure on the fuel in the chamber will vary with plunger displacement, plunger velocity and the rate of injection of the fuel through the delivery valve, according to Equation (5-6) [183].[167].

$$P_P = \frac{B_P}{(V_{pc} - A_p d_p + A_{dv} d_{dz})} (V_p A_p - Q_p - v_{dz} A_{dv}) \tag{5-6}$$

, where P_P is the pressure inside the plunger, V_{pc} is the maximum plunger volume, d_p is the plunger displacement, d_{dz} is the displacement of delivery valve, V_P is the instantaneous plunger volume, Q_P is defined in Equation (5-5), v_{dz} is the velocity of delivery valve, A_{dv} is the area of delivery valve. The bulk modulus of the fuel, B_P, is defined by Equation (5-7).

$$B_P = \rho a^2 \tag{5-7}$$

Where B_p is bulk modules of fuels, ρ is the fuel density which have been measured from biodiesel and biodiesel blends (WCO), a is the local speed of sound which is given by Equation (5-9).

$$a = 4.69P + 1330 \tag{5-8}$$

5.4.1.2 Characteristic Delivery Valve Chamber Equations

The delivery valve is situated at the end of the plunger chamber. The delivery valve, which consists of a conical sealing element, opens and varies the effective area by which the fuel can enter delivery valve chamber. The delivery valve characteristics such as opening pressure, effective flow area and residual line pressures are as shown Figure 1-1 . The barrel of the plunger encloses its fuel injection delivery valve and an optional snubber valve assembly. For smooth fuel flow the suction valve must have an adequate free area and the delivery valve spring must exert a lower spring force than the needle valve spring, (see Appendix of mathematical mode).

In general, and especially at full load, the delivery valve lift which controls the orifice area increases with the engine speed, which allows a greater quantity of fuel through the cross-sectional area of the valve through which the fuel flows vary with the amount of force exerted by the pressure within the chamber against the spring delivery valve.

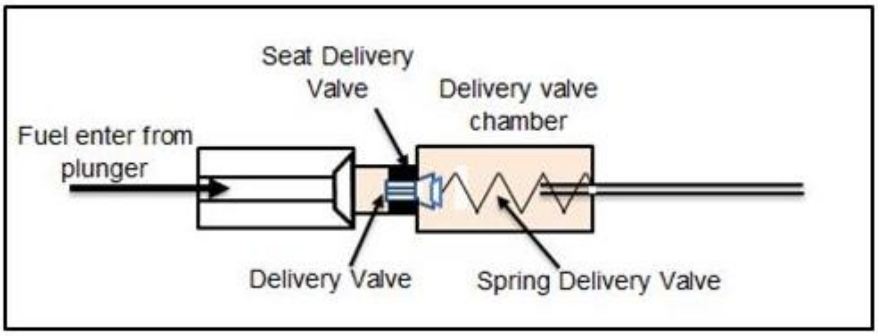


Figure 5-3 Scheme of mechanical fuel delivery valve line

The geometric cross-section area of the delivery valve is shown in Figure 5-4. More information on the assembly of the delivery valve can be found in Section 6.1.3.2.

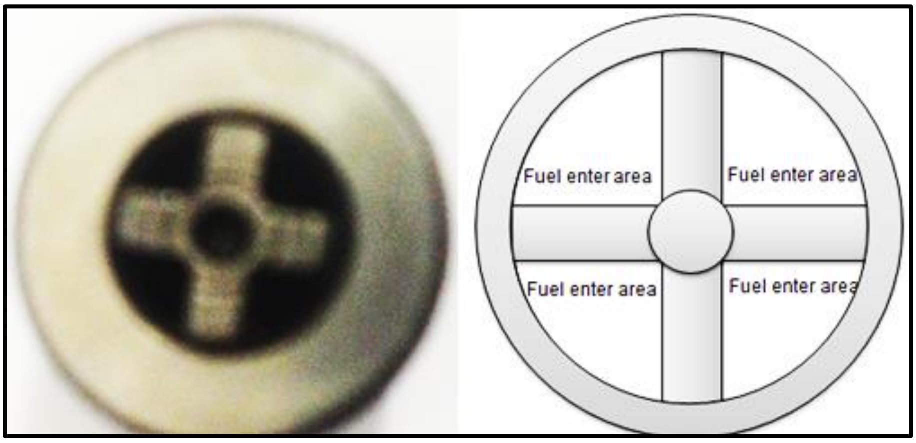


Figure 5-4 Scheme fuel delivery valve area

The cross-sectional area of the delivery valve is given by Equation (5-9).

$$A_{ax} = A_{dv} - d_{dz}(A_{dv} - A_{dvf})/L_m) \tag{5-9}$$

Where A_{ax} Effective flow area of the delivery valve, A_{dv} is the cross-sectional area of fuel, d_{dz} delivery valve movement A_{dvf}, L_m length of delivery valve, The volume of delivery valve chamber is calculated with Equation (5-10).

$$V_{dv} = A_{ch} L_{ch} \tag{5-10}$$

V_{dv} Volume of delivery valve chamber, A_{ch} area of the delivery valve chamber, L_{ch} length of delivery valve chamber, The fuel delivery valve data for the basic equations are presented in Table 5-2.

Table 5-2 Data of fuel delivery valve

Valve diameter	3 mm
Opening pressure	172 + 3 - 0 bar
Maximum displacement	2 mm

The motion of the delivery valve is controlled primarily by the flow of high pressure fuel. The dynamic behaviour of the fuel flow is deduced by considering the basic features of the fuel delivery valve as an injection system in which the fuel flow rate through the delivery valve is based on difference in pressure between plunger and delivery valve, the rate of fuel entry to the delivery valve is modelled using the general Equation (5-11).

$$Q_{Pd} = C_q \; A_{ax}\sqrt{\frac{2}{\rho}} \; (P_{dv} - P_p) \tag{5-11}$$

Where Q_{Pd} is the flow rate through delivery valve, A_{ax} is the cross-sectional area of the delivery valve, P_{dv} is Pressure at the delivery valve, P_p is pressure exerted by the plunger, C_q is the flow coefficient, and ρ is the fuel density

The delivery valve displacement, d_d, is given by Equation by Equation (5-13).

$$d_d = \left(f_s - k_{ds}\; d_z - \left(d_z \; d_{max}\right) \;\; k_{dc} - v_{dz} \;\right) / \left(m_{dv}\right) \tag{5-12}$$

d_d Delivery valve movement, f_s spring force, k_{ds} spring stiffness's d_z valve displacement, $d_{\max dv}$ maximum valve displacement k_{dc} damping ratios, v_{dz} valve velocity m_{dv} delivery valve motion

The fuel delivery valve displacement is equal to the volume change due to the motion of delivery valve allowing for compressibility in the delivery valve chamber and flow into the injection pipe.

Equation (5-13) describes the process whereby the delivery valve chamber pressure and valve movement is related to the fuel delivery valve injection rate less the rate of flow into the injection fuel pipe [167].

$$P_d = \frac{B_d}{\left(V_{dch} - A_{ax}\ d_d\right)}(\ Q_{pd} - Q_d\ v_{dz}\ A_{ax} - \ Q_{pk}\ ) \tag{5-13}$$

, where P_d is the pressure at the delivery valve v_{dz} is the velocity of the flow through the delivery valve, Q_{pd} is the fuel injection rate into the delivery valve, Q_d is the fuel injection rate into the delivery valve chamber, Q_{pk}

5.5 Fuel Injection Pipeline Model

The high pressure fuel injection pipe connects the fuel injection pump to the fuel injector and relevant data is shown in Table 5-3.The flow of fuel through the fuel injection pipe is related to the pressure in the delivery valve chamber and fuel injector, as described by Equation by Equation (4-14).

$$P_l = \frac{B_l}{(V_l\ )}(\ Q_{dv} - Q_l - Q_{ll}\ ) \tag{4-14}$$

Where P_l is the pressure in the fuel injection pipe, B_l is the bulk modulus of each fuel. V_l is the volume of pipeline fuel injection Q_{dv} is the flow rate of the fuel delivery valve, Q_l is the flow rate of pipeline fuel injection and Q_{ll} is the leakage flow rate.

Table 5-3 Data of fuel injection pipeline

Pipe internal diameter	2 mm
Pipe length	450 cm

5.6 Fuel Injector Dynamic Model

The main role of the fuel injector in a diesel engine is to spray fuel into the combustion chamber at the correct time for the correct duration, see Figure 5-5. The needle of the injector valve opens when the fuel pressure acting on the tapered face of the needle valve exerts a sufficient force to overcome the spring compression. The fuel enters into a lower chamber, is forced out through a series of tiny holes into the combustion chamber. With the outflow of fuel there is then a drop in pressure which allows the spring to return the needle valve to the initial, closed, position. There is, thus, a mechanical impact as the needle closes the valve, which is called the injector tick [138].

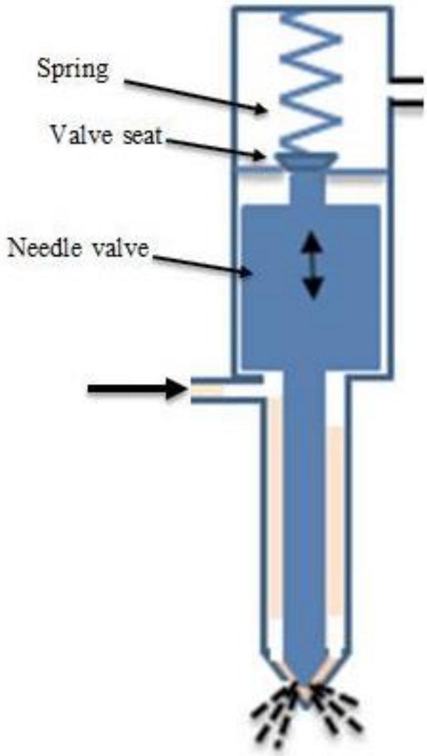


Figure 5-5 Schematic of fuel injector of diesel engine

There is an impact between the needle and valve seat when the fuel first enters the injector and pushes the needle upwards. There is some out flow of fuel through the injector holes during this build-up of pressure in the injector. However, by the time of the mechanical impact between the needle valve and its backstop and there is full fluid flow through the nozzle fuel injector. The closing of the needle valve is very fast with little flow through the holes. Finally, there are back-pressure fluctuations in the fuel pipeline which are repeated reflections of the back pressure pulses in the fuel delivery line after the valve between needle and fuel injection pump plunger has closed [123].

5.6.1 Characteristic Fuel Injector Equations

In the fuel injector, there are small holes sized to atomise the fuel, to break the fuel flow into tiny drops which, when sprayed into the engine combustion chamber, are ready to ignite. As stated above the first impact collision of the needle indicates the instant when the needle reaches its fully open position. Similarly, the first collision when the needle is moving to stop the flow of fuel indicates the instant when the needle first returns to its seat [172, 184].

The fuel injector is modelled as a spring-mass-damper system, where the external force is the sum of the hydraulic forces acting on the valve injector needle. Newton’s second law of motion is applied to determine dynamic valve lift and valve motion as function of inertia, mass spring rate, damping pressure drop, pressure set spring, etc. Basically a force balance equation is used to determine the dynamic valve lift and the needle life velocity according to Equation (5-15). Data concerning the fuel injector is shown in Table 5-4.

$$d_{nz} = \left(f_n - k_n\ d_n - (d_n - d_n\, max)\right)\ k_c - v_n / \left(m_n\right) \qquad (4\text{-}15)$$

d_{nz} Displacement of needle valve , f_n spring force of left needle, k_n spring stiffens, d_n Displacement of needle valve, v_n velocity of needle injector valve m_n Mass of needle injector valve,

Table 5-4 Data of engine fuel injector

Opening pressure	180 + 3 - 0 bar
Holes number	6 holes
Hole diameter	2.136 µm (micro-meters)
Needle lift	0.35 mm

There are many benefits associated to using type of this model. That's possible to assess fuel injector behaviour for a range of fuel flow rates through to injector holes into the engine cylinder, see Equation (5-19).

$$Q_{ing} = C_q\ A_{ing} \sqrt{\frac{2}{\rho}}\ (P_{ing} - P_{cy}) \qquad (5\text{-}16)$$

C_q Discharge coefficient, A_{ing} Area of holes, ρ Fuel density, P_{ing} Nozzle chamber pressure, P_{cy} Cylinder pressure, the Fuel injector chamber pressure process with needle valve movements related to the fuel injection rate and velocity of needle injector with the leakage injector flow rate described by Equation (5-20) [185].

$$P_{ing} = \frac{B_{ing}}{(V_{ing} + V_{sac} + A_n\ d_{nz})}\ (Q_{li} - Q_{inj} - v_n\, A_n) \qquad (5\text{-}16)$$

P_{ing} Fuel injecting pressure, B_{ing} Bulk modules is the bulk modules of the fuel and varies with injection pressure according to Equation 5-8, V_{ing} is the volume of the injector, V_{sac}

Volume of sac, d_{nz} displacement of needle valve, Q_{li} fuel injection rate of pipe Q_{inj} fuel injection rate into cylinder, $Q_{\lg n}$ fuel injection rate leakage, v_n injector needle velocity.

5.7 Simulation Procedures

The solving of the difference equations based on numerical approximations was done using a MATLAB program. As described in Section 5-2, the methodology introduced in this model suggests a newly developed approach towards analysing the impact analysis of fuel injection in diesel engines. The method is based on fundamental relationship between fuel injection parts such as fuel injection pump and fuel injector, which is divided into four parts for one loop equations working such as pump plunger, fuel delivery valve, fuel line and fuel injector Figure 5-6 is a schematic representation of the fuel injection procedure, from cam rotational to the closure of the injector nozzles and the cutting off of the fuel supply to the engine cylinder.

However, this mathematical model was set up for two engine speeds 1300 and 1600 rpm, at four loads with four different biodiesel blends (B0, B20, B40 and B100). The fuel injection dynamic model of the motion of the delivery valve and needle injector has been developed, incorporating contact stiffness and material and fluid damping properties This dynamic model has been found to be useful in investigating delivery fuel valve and needle valve impact behaviour with different fuels and in the correlation of predicted and measured vibration response with fuel injection pressure and vibration of the fuel injection pressure with fuel properties. The dynamic model has also enabled to detrimental effects of conventional intrusive delivery valve and needle lift movements to be examined.

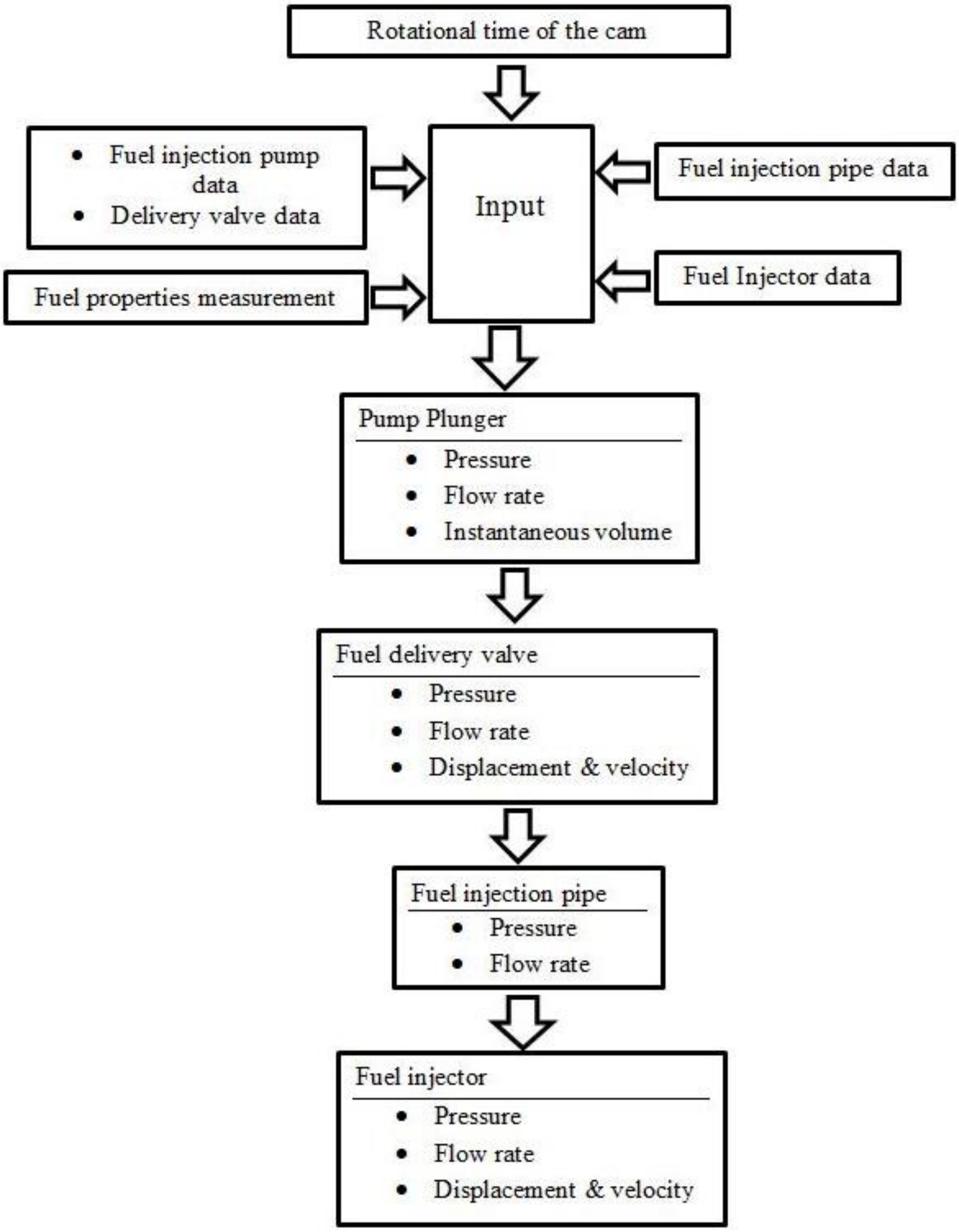


Figure 5-6 Scheme of fuel injection system simulation

5.8 Simulation Results and Discussion

The validity of the developed fuel injection model was tested for 8 test conditions using different fuel pump and injector operating regimes under two engine speeds of 1300 rpm and 1600 rpm. On average the simulation was found to show similar trends for the behaviour of fuel pressure, impact response of fuel delivery valve and injector needle valve.

5.8.1 **Fuel Properties with Variation Fuel Injection Pressure**

This section reports the investigation of variations in the fuel injection process to changes in important properties of biodiesel blends, including density and bulk modules. In Figure 5-7 (a) and (b) shows variation in fuel injection pressure with bulk modulus and fuel density. It can be seen that the density and bulk modulus of the biodiesel are higher the higher the proportion of biodiesel present. It can also be seen that the density and bulk modulus increase monotonically with increase in fuel injection pressure. For the all fuels tested such as biodiesel and biodiesel blends, the bulk modulus and fuel density increased linearly with fuel injection pressure and for each parts of fuel injection system pressure range studied, the bulk modulus and fuel density of biodiesel and biodiesel blends, its higher comparing with diesel fuel. These results concur with those reported in the literature review [186].

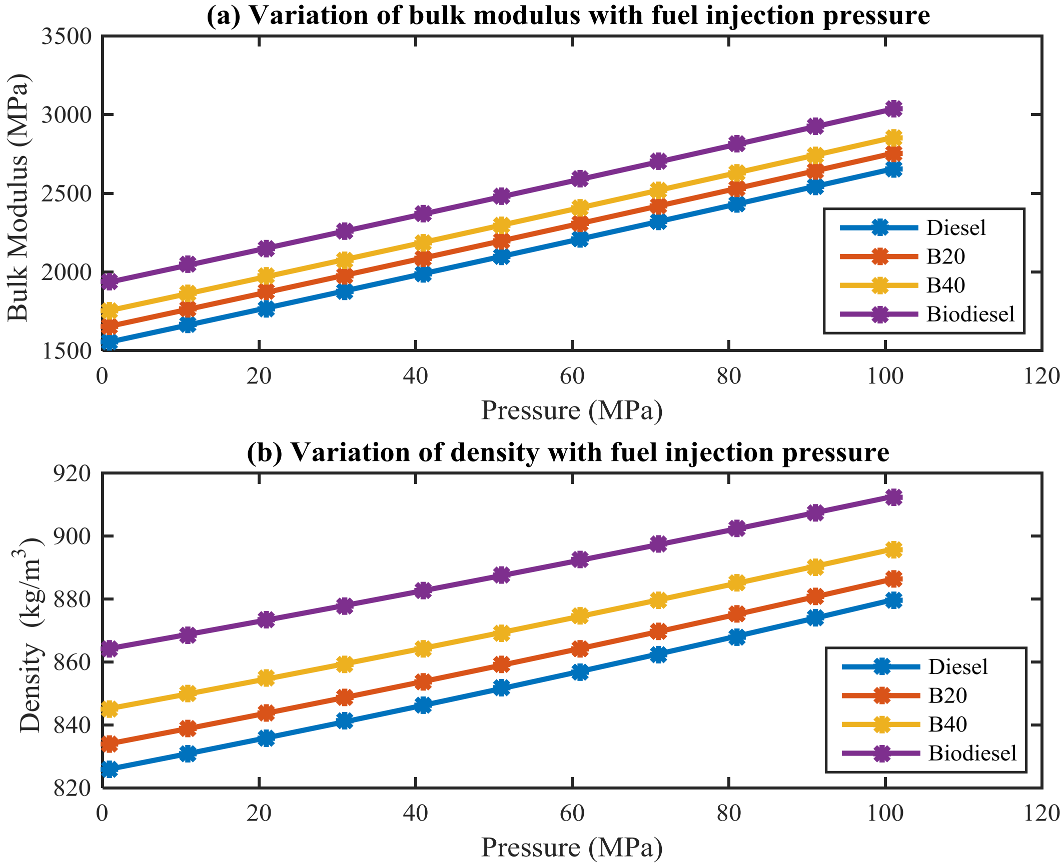


Figure 5-7 Simulation of variation of (a) fuel bulk modulus, and (b) fuel density for different biodiesel blends with fuel injection pressure.

5.8.2 Variation of Fuel Injection Pressure and Pressure Parameters

The model’s predictions of fuel injection pump pressure and fuel injector pressure, as a function of cam angle, are shown in

Figure **5-8**. The waveforms of both fuel injection pump pressure and fuel injector pressure show similarity with results reported in the literature review (Section 3.2.1.1) and experimental result reported in Section 7.1. The fuel injector pressure is delayed compared to the fuel injection pump pressure, but rises to a higher value. That is in accord with the compressibility of the fuel, velocity of sound in the fuel, spring forces, reflected pressure waves, etc. and confirms results obtained in previous work [187, 188]. Fuel injection system pressures such as pump plunger, delivery valve, pipeline fuel injection and injector needle valve have been calculated and plotted in Appendix of mathematical.

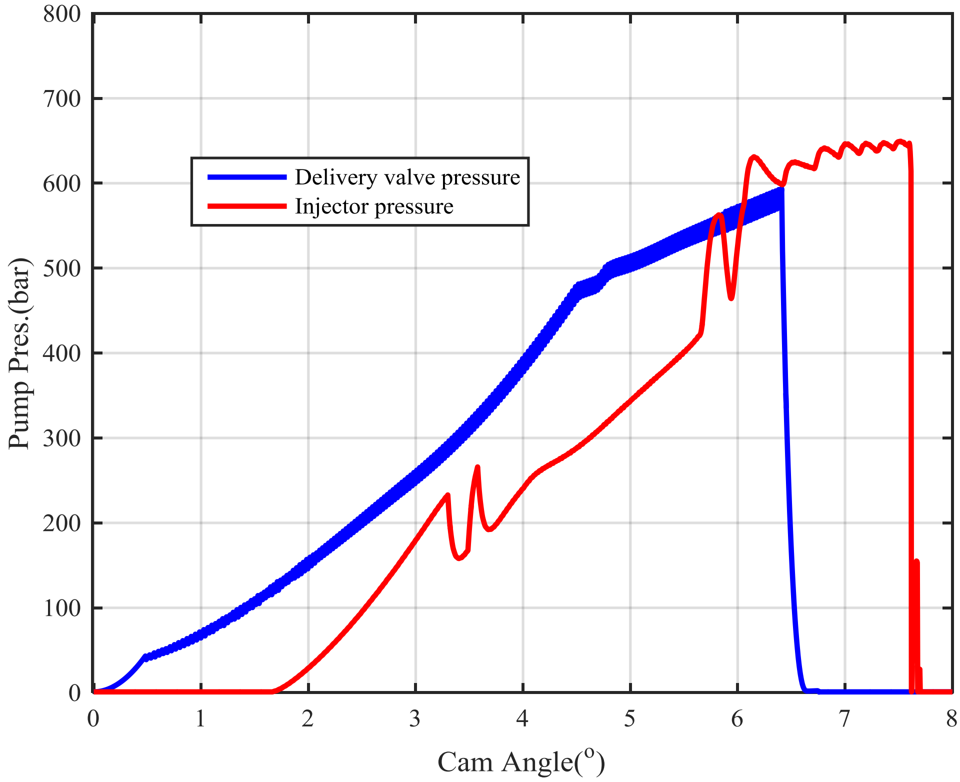


Figure 5-8 Fuel injection pump pressure with fuel injector pressure

Figure 5-9 show the fuel injection pump pressure at an engine speed of 1000 rpm under different loads and four different biodiesel blends, B0, B20, B40 and B100. The results show the pump pressure increasing with injection fuel duration when increasing the engine load. Also, the lower the proportions of biodiesel have higher the pressure amplitude. The trend represented by the predicted results is similar to the observed experimental result, see chapter 7.

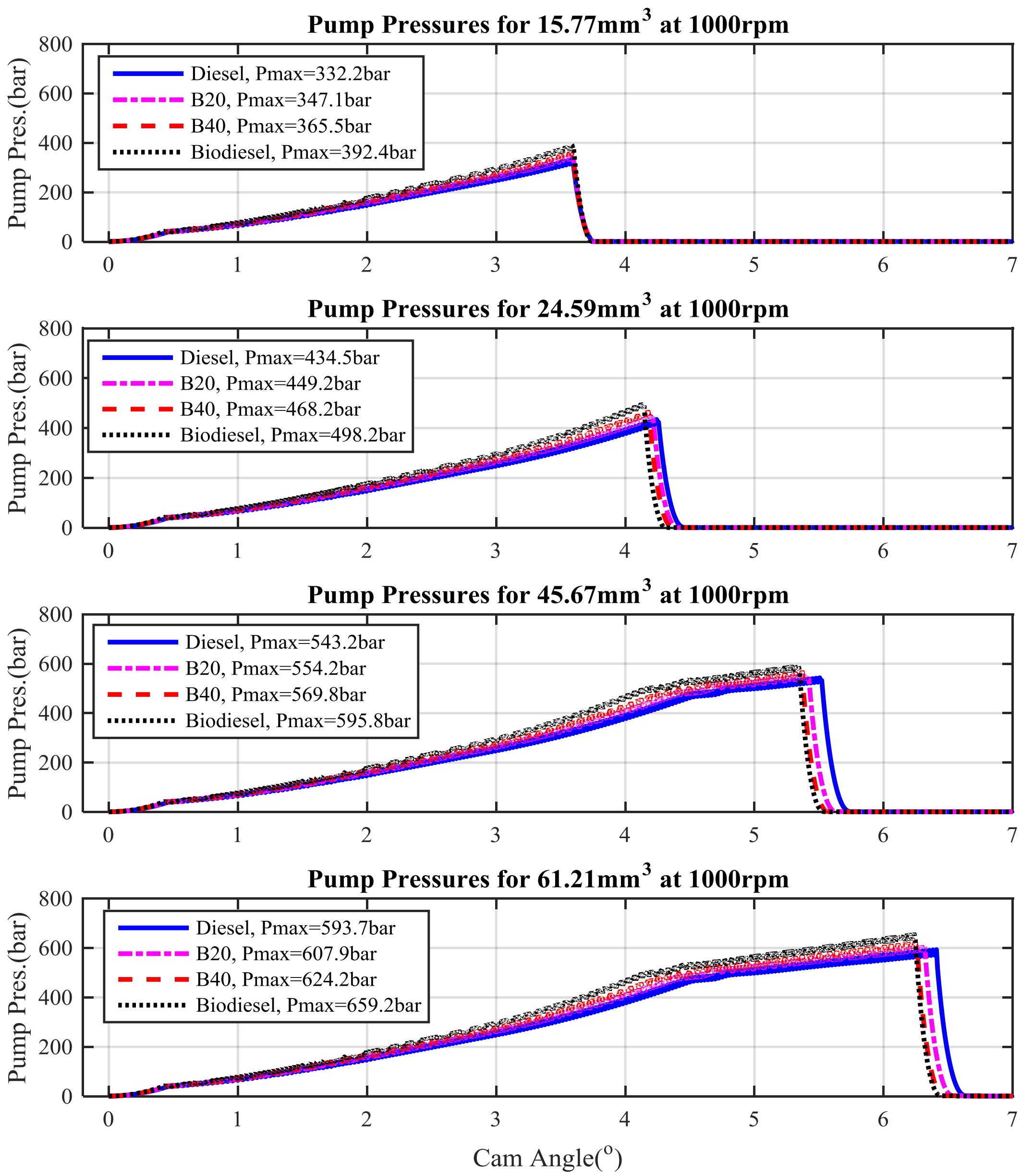


Figure 5-9 Fuel injection pump pressure as a function of cam angle for biodiesel blends B0, B20, B40 and B100

Figure 5-10 shows the greater the load and the higher the proportion of biodiesel in the blend the greater the peak pressure. The same trends are observed with the duration of the injection period, but here the effect of proportion of biodiesel is small and may not be significant. The reason suggested for these trends is the higher bulk modulus, density and compressibility of biodiesel leads to changed beh4 66viour in fuel injection system even the biodiesel fuel density is higher which effected to bulk modules. These predicted results have been tested experimentally, see chapter 7.

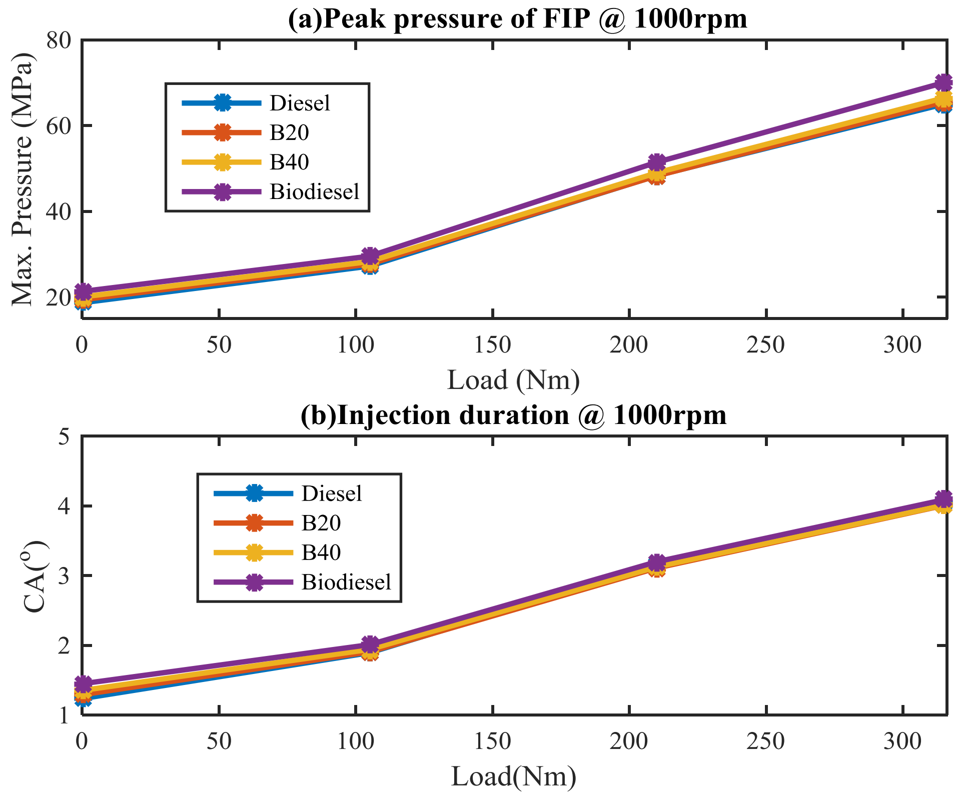


Figure 5-10 Peak pressure and injection duration at 1000 rpm as a function of load for biodiesel blends B0, B20, B40 and B100

Figure 5-11 shows fuel injection rate under different load at 1000 rpm with different fuels. The results show the fuel injection duration and hence rate increase with different engine load increasing with the engine load increased, showing agreeable results with engine fuel demand with load.

However, biodiesel and its blends show a significant advanced fuel delivery while the overall duration is relatively the same across different fuels. Therefore, it can be understood that the advanced fuel delivery is one of the main reasons that biodiesel exhibit an altered the combustion performances compared with that of standard diesel.

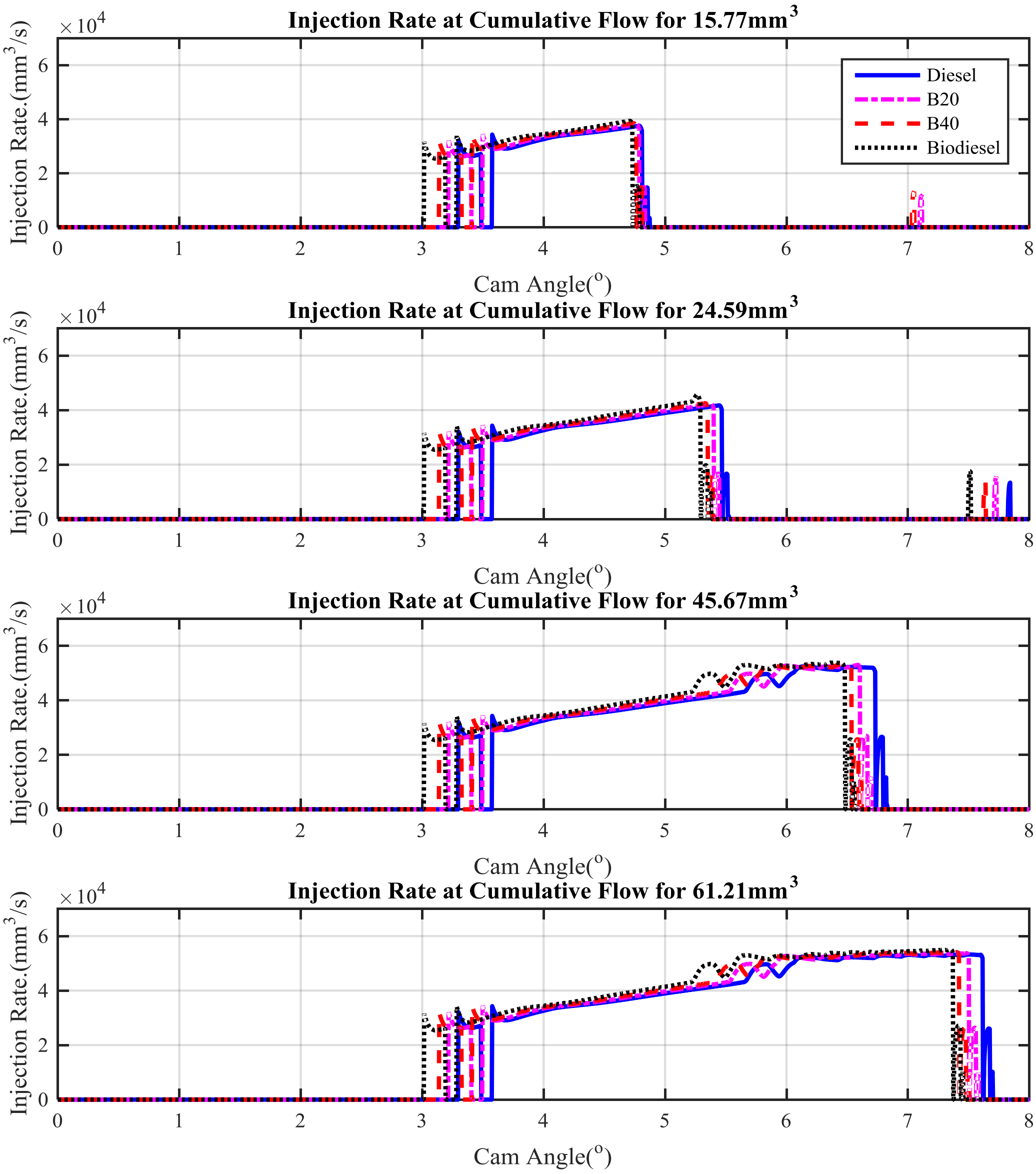


Figure 5-11 Fuel injection rate as a function of cam angle for biodiesel blends B0, B20, B40 and B100

5.8.3 Vibration Responses

To analyse and understand the system of mechanical vibrations, it is important to understanding the relationship between vibration parameters such as velocity, displacement and acceleration. The displacement is defined as a measure of the distance that a vibrating component moves. Velocity is defined as a measure of the speed of motion of a component vibrating. Acceleration is defined as a measure of the change rate of the velocity of a component vibrating [189]. In this research, the vibration features of interest are the displacement and velocity of the delivery fuel valve and injector needle valves. Especially, the latter can be an effective measure of the strength of mechanical impacts between the valve moving element and the seats.

Figure 5-12 shows the displacement of delivery valve and injector needle valve movement. The results show the injector needle valve have high amplitude than fuel delivery valve which prove by pressure in section previous section. Also, when increasing the fuel quantity with engine loads and speeds increasing the movement of delivery valve and injector needle valve, which more forces by pressure on fuel injection to open more area for fuel into combustion chamber. Therefore, the results of velocity of delivery valve and injector needle valve showed the same results of displacement as shown in appendix results of mathematical.

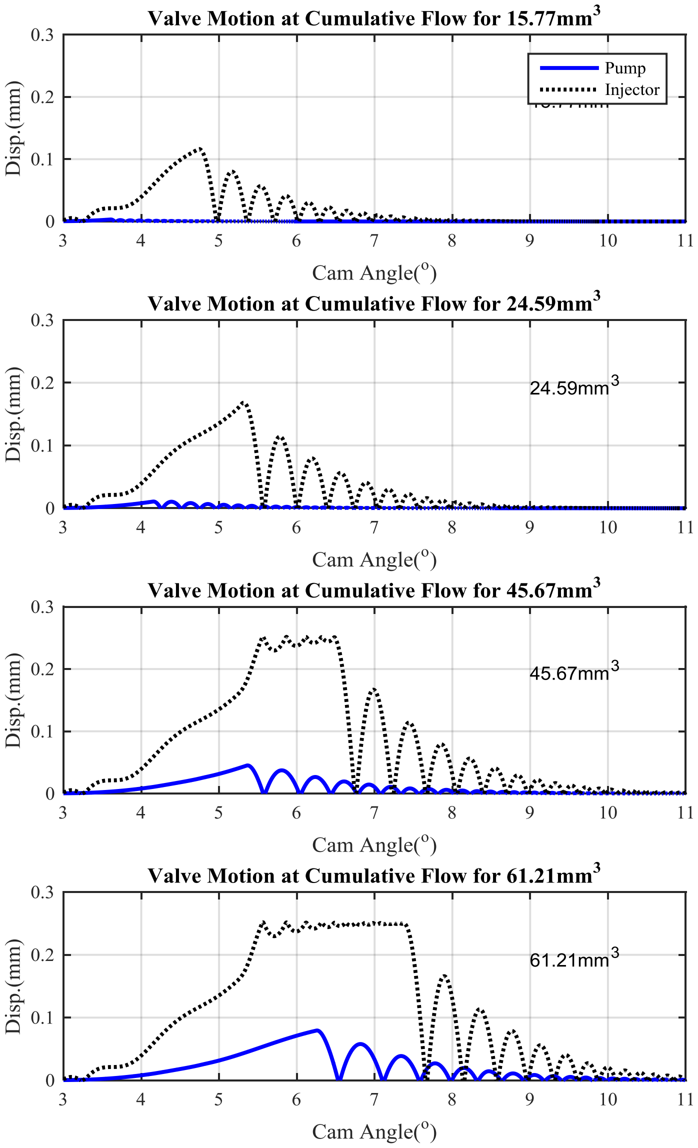


Figure 5-12 Displacement of delivery and injector needle valves as a function of cam angle for different fuel flow rates.

The impact of the delivery valve for different biofuel blends was predicted by the model and the results plotted in Figure **5-13** which shows the velocity of delivery valve movement for an engine speed of 1000 rpm. It can be seen that the velocity of the delivery valve (and hence the impact force it generates) decreases slightly with an increase in the proportion of biodiesel in the blend, with a consequence for the valve impact experienced with the different blends. Increasing injection pressure increases the quantity of fuel forced through the injector. It can also be seen that the larger the "cumulative flow" the greater the valve velocity.

Moreover, the figure also shows that the higher the proportion of biodiesel the more advanced is the valve motion and, hence, the more advanced the valve impact. These effects are also seen in the experimental result. Therefore, it is feasible to predict the fuel dynamics by the external vibration responses.

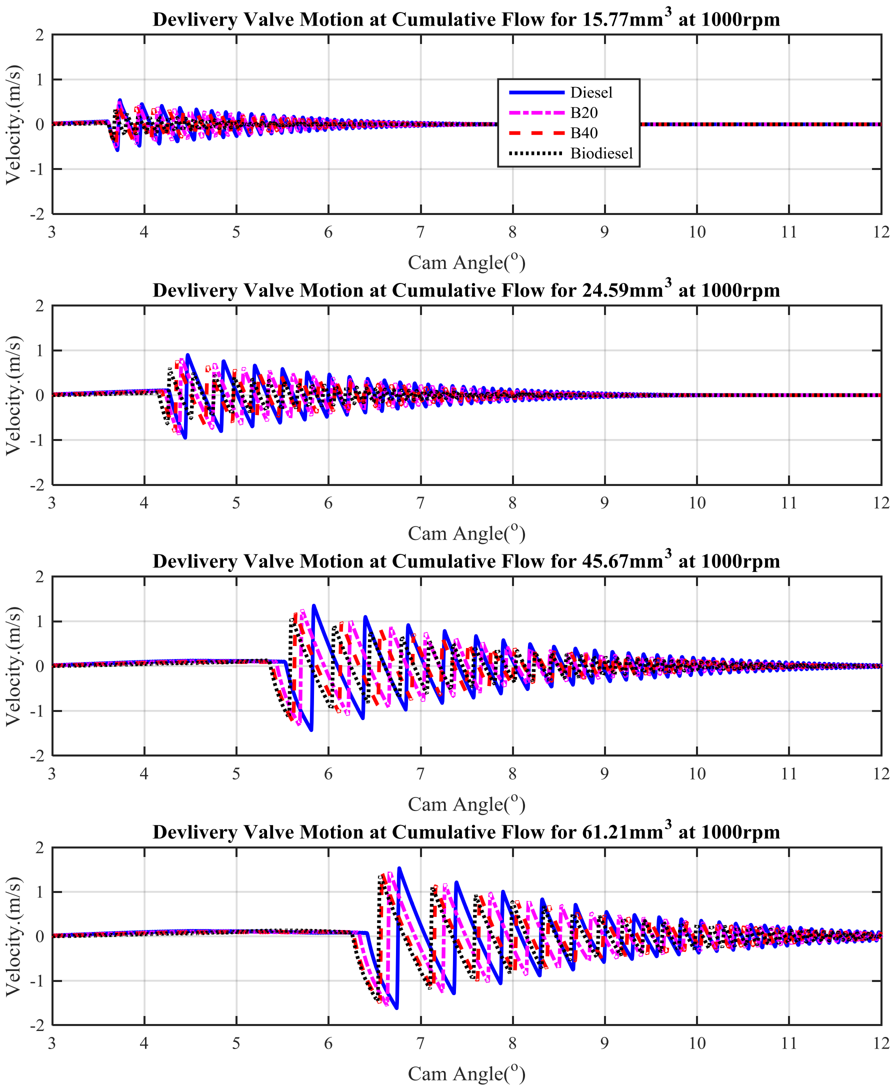


Figure 5-13 Delivery valve velocity as a function of cam angle for biofuel blends, B0, B20, B40 and B100, under different loads

5.9 Summary

The properties of the fuel have great impact on the fuel injection characteristics. For this reason, an improved mathematical model for numerical simulation of the injection processes has been developed to investigate the consequences of using different blends of biodiesel on the fuel injection equipment. The model has been tested under several operating regimes where different operating regimes were simulated. The predicted results are compared to experimental tests in Chapter 7.

This chapter has also presented the principles of dynamic fuel injection processes of a diesel engine from which the model was derived. The model predicts the fuel injection pressure, delivery valve pressure, fuel injection pipeline pressure and fuel injector needle pressure. The model also predicts velocity and displacement of fuel delivery valve and injector needle valve for different biodiesel blends and shows these dynamic features correlates well with the fuel flows and hence paves the ways for using vibration responses for monitoring and diagnosing fuel injection and its associated equipment.

CHAPTER SIX

6 INSTRUMENTATION OF TEST RIG AND ENGINE TEST PROCEDURES

This chapter gives a detailed description and information of the facilities required for the operation of the test engine running with different fuels. Engine specifications, including fuel injection characteristics are provided and the details of the high pressure fuel injection system are described. The instrumentation and procedures for measuring the density, kinematic viscosity and lower heating value of the biodiesel fuels is described, as is the data acquisitions system and application software. The test procedures are described in detail and the appropriateness of the test procedures and methodology are discussed.

6.1 Test Facilitates

6.1.1 Engine Test Rig Dynamometer Specifications

To study the effect of biodiesels and evaluate vibration based diagnostics, a heavy-duty, direct injection, turbocharged, four strokes, four cylinders JCB diesel engine is employed, which was setup in the Automotive Laboratory, University of Huddersfield (UoF), UK. This engine is commonly used as a power supply for wheel loaders, excavators, soil compactors, electric generators, etc. The diesel engine test rig is connected to a 200 kW AC Dynamometer 4 Quadrant Regenerative Drive, with motoring and absorbing capabilities

This test rig was fully instrumented (see below for details), and the steady state cycle was programmed using CADET V14 software integrated within the engine system operation, which was controlled from a panel control outside of the engine room. Also integrated into the measurement system are pressure transducers, thermocouples, air flow metres, fuel flow metres, a shaft encoder in-line torque meter and emission measurement instrumentation. Specifications of the experimental facilities specific to the diesel engine are listed in Table 6-1, and shown in Figure 6-1.

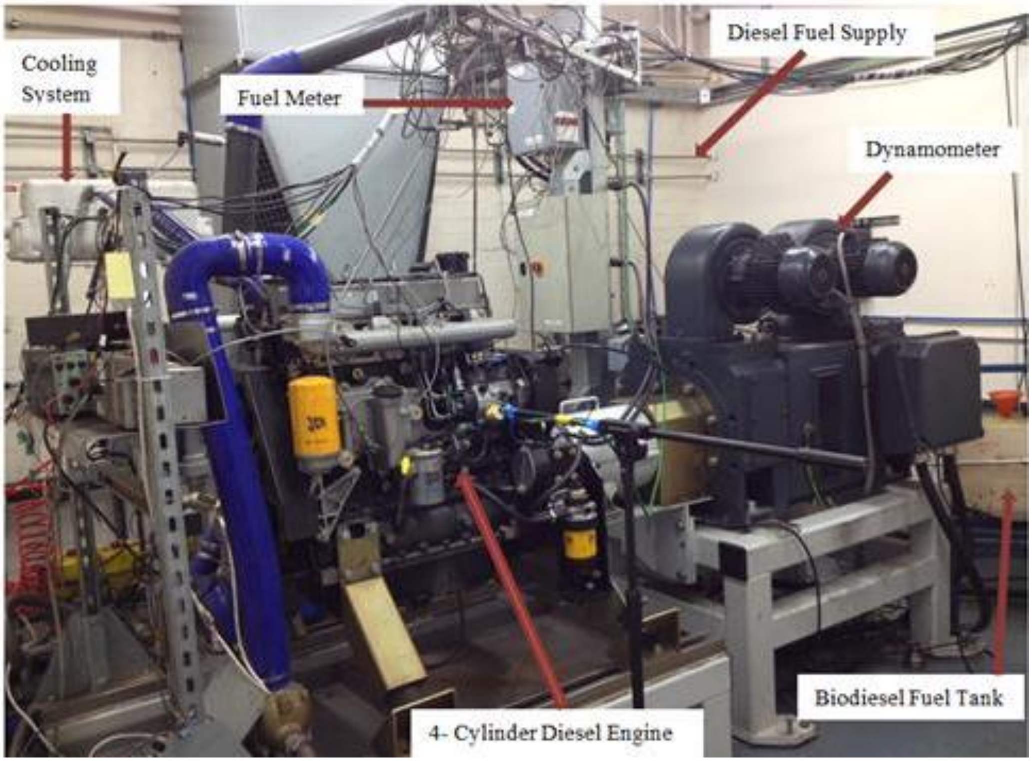


Figure 6-1 Test rig experimental engine facilities

Table 6-1 Specification of engine test rig

Diesel Engine Type	JCB 444 Turbo charged diesel engine
Number of cylinder	4
Number of valve	16
Inlet valve diameter	36.5mm
Exhaust valve diameter	33.2mm
Combustion cycle	4 - stroke
Fuel injection system	Direct injection
Cooling system	Water
Displacement	4.40 litres
Fire order	1-3-4-2
Stroke	132 mm
Bore	103 mm
Compression ratio	18.3:1
Maximum speed	2200 rpm
Maximum load	425 Nm @ 1300 rpm
Fuel injection pump	Rotary mechanical

6.1.2 Engine Coolant System

The engine system of water cooling was fitted to the diesel engine test rig. However, to avoid the engine in cold starts condition and to assistance maintain the engine running temperatures, the test rig facility has had two Eltron Chromalox oil heaters mounted in the engine sump and one Watlow industries 3kW domestic immersion water heater mounted within the coolant circuit. That can be activated without the need to have the engine running because it had dedicated pumps. The both of oil circuits and coolant contained thermostatically controlled by valves system, which is can be allowed the fluids circulated only in until of the test rig by set temperature of 90 °C was reached.

Table 6-2 Specification of engine cooling system

Engine coolant capacity	7 litres
Water pump flow rated speed	200 litres/ min
Maximum pressure in the cooling circuit	1 bar
Maximum temperature of cooling liquid	$110\,C^0$
Coolant specification approved	ASTM D6210 [190]

However, if the oil or coolant temperatures surpassed this limit, the respective thermostats opened and the fluid was diverted through two separate heat exchangers, where heat generated by the engine was transferred to a constant water supply from cooling tower. This system created to replace the standard radiator of vehicle. The layout of the test rig cooling system has been described in Table 6-2.

6.1.3 Engine Fuel Injection System

The high pressure fuel injection system of the test engine including a rotary distributor fuel injection pump, injection pipeline and fuel injector is shown in the photo presented as Figure 6-2. The system shown is in-line direct injection. The rotary distributor fuel injection pump has a single plunger for distributing fuel to each cylinder. This system is monitored by measuring fuel injection pump pressure, fuel injector pressure and fuel injection pump vibration. Further information on each of these is given later in this chapter.

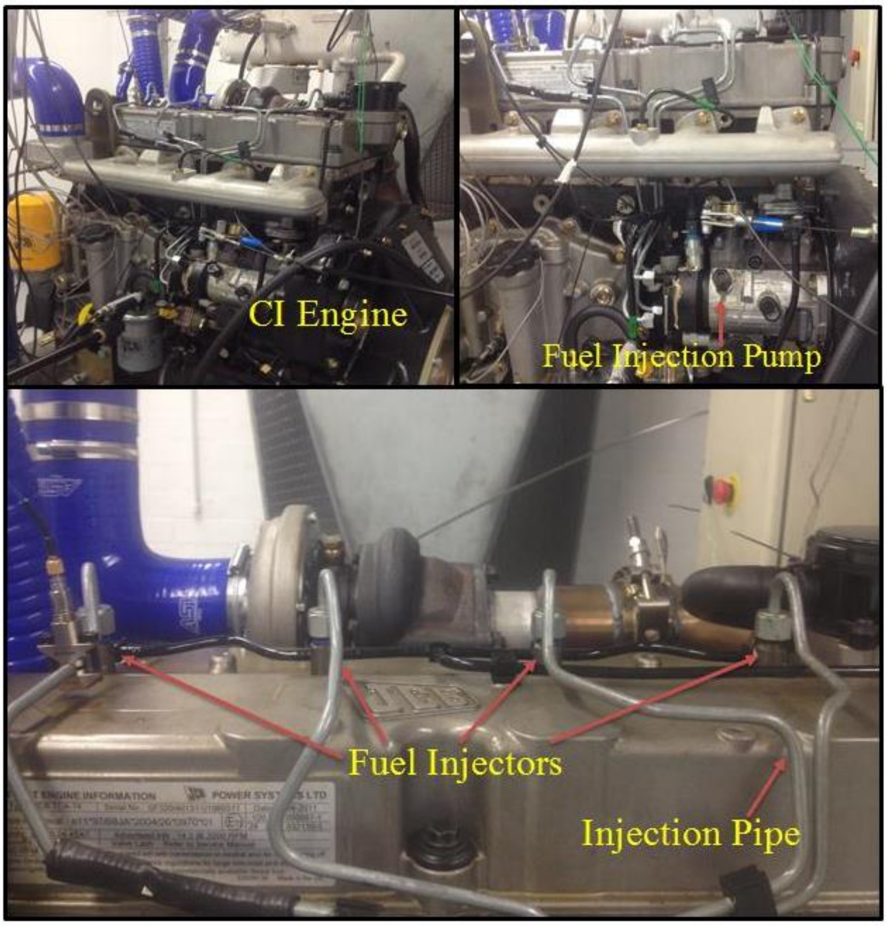


Figure 6-2 Fuel injection system FIP, injection pipe and fuel injector

6.1.3.1 Fuel Injection Pump

The fuel injection pump supplies the fuel into internal combustion engine through the pipeline and injector. The engine test rig has a rotary distributor fuel injection pump single plunger. The specification of fuel injection pump is described on Table 6-3. The fuel injection pump is in contact with the cam shift to work with sequence engine fire. There is more information for the pump fuel delivery valve in next section.

Table 6-3 Fuel injection pump specification

Rotary distributor fuel injection pump	Delphi DES /10130DEG
Number of injections	4
Plunger diameter	7.0 mm (4 off).
Delivery valve opening pressure	172 + 3 - 0 bar.
Boost stroke	5.9 to 6.1 mm.
Fuel pipe diameter	2 mm

6.1.3.2 Fuel Delivery Valve of Rotary Distributor Fuel Injection Pump

The fuel delivery valve of a rotary distributor fuel injection pump (Delphi DES /10130DEG) is shown in Figure 6-3. The fuel injection pump single plunger has four injection delivery valves each of which has a snubber port, and each snubber port has its own fuel delivery valve. The individual valve springs were tested as described in Appendix.

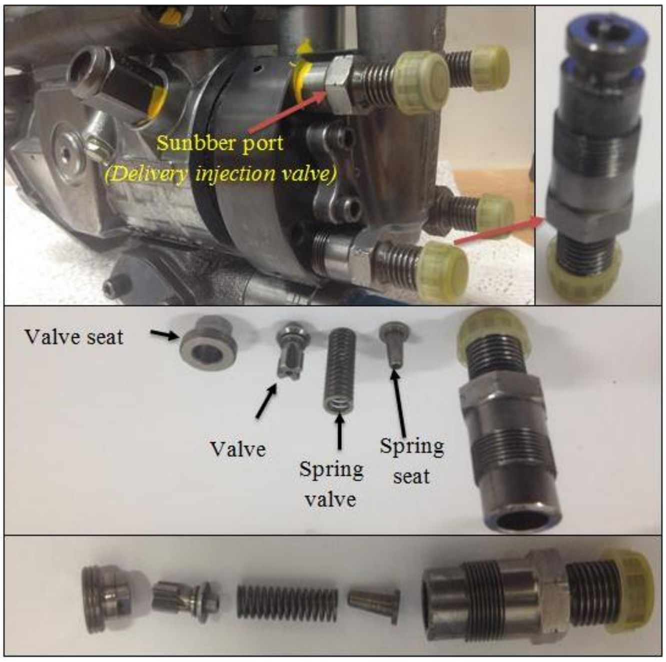


Figure 6-3 Snubber port or fuel delivery valve chamber

6.1.3.3 Fuel Injector Assembly

Fuel injector (Delphi IJBB04101A JGM) used to spray the fuel into combustion chamber is a direct replacement for diesel engine JCB 444 and is specifically designed for use with high-pressure. Table 6-4 shows the more important components of the fuel injector; needle valve, spring valve and spring seats. The injector valve springs were tested as described in the Appendix. Figure 6-4 shows fuel injector such as needle valve, spring valve and spring seats. The injector valve spring has been tested as more information in the Appendix.

Table 6-4 Fuel injector specification

Fuel injector	Delphi B04101A
Holes number	6 holes
Hole diameter	2.13.6 µm (micro-meters)
Needle lift	0.35 mm

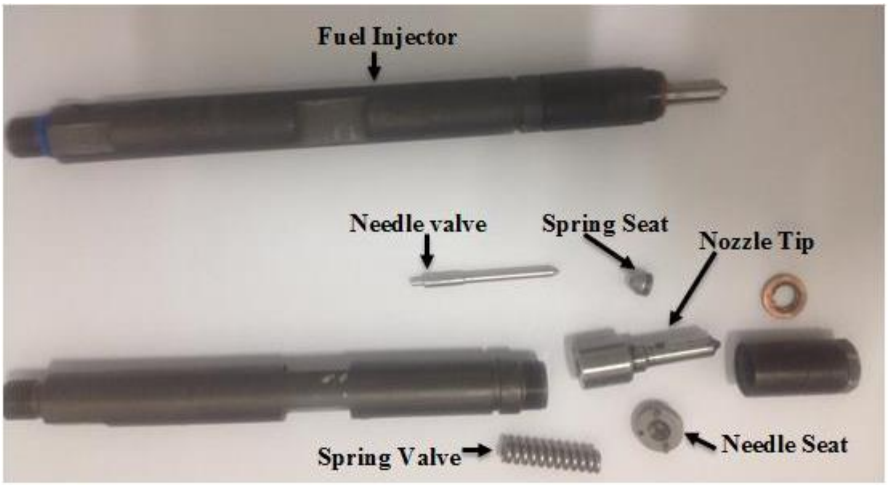


Figure 6-4 Fuel injector assembly

6.2 Pressure Measurement Instrumentation

6.2.1 Fuel Injection Pump Pressure Sensor

A CA-YD-124 piezo-electric pressure sensor was used to monitor the FIP pressure. The sensor was mounted close to the FIP in the first injection pipe, see Figure 6-5. The signal was passed through a YE6261B charge amplifier with output sensitivity 25.07mv/MPa. The sensor pressure range was 0 to 200 MPa.

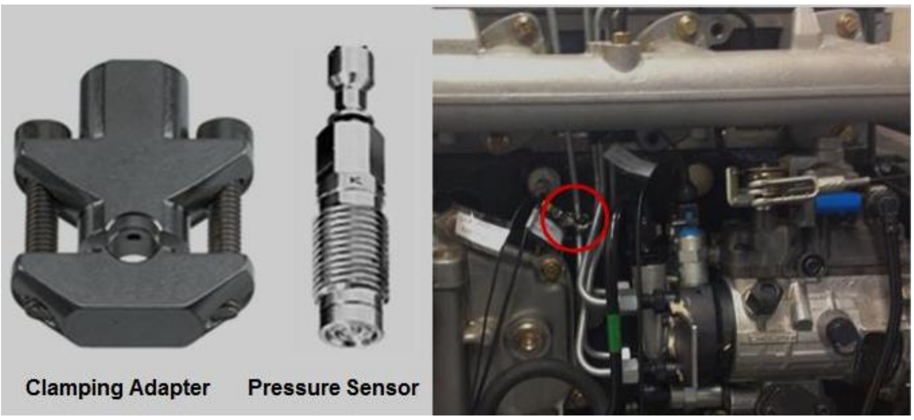


Figure 6-5 Fuel injection pump pressure sensor installation and position

6.2.2 Fuel Injector Pressure Sensor

The same piezo-electric pressure sensor and charge amplifier (CA-YD-124 and YE6261B respectively) were used to monitor or measuring of fuel injector pressure in micro-second mounted on the pressure pipe close to the cylinder block, seen **Error! Reference source not found.**, As above, the pressure sensor range was from 0 to 200 MPa, though the sensitivity of the charge amplifier was moderated to 50 mv/MPa.

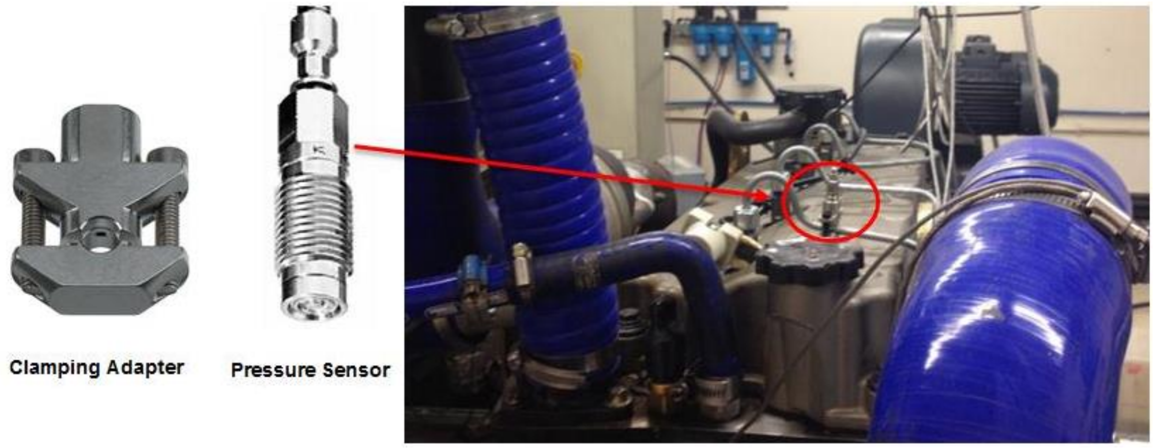


Figure 6-6 Fuel injector pressure sensor installation

6.2.2.1 In-cylinder Pressure Sensor

To monitor the engine combustion, cylinder pressure a Kistler112A05 piezo-electric sensor was used, see Figure 6-7, this sensor is capable of working satisfactorily under high temperatures and providing precision measurement of in-cylinder pressures for internal combustion engines. In this research just one sensor was used to mount in the first cylinder in combustion chamber. The Kistler112A05 was connected to a Bruel & Kjaer type 2635 charge amplifier to give an output of 0-10 Volts for the calibrated pressure range of 0-25 MPa.

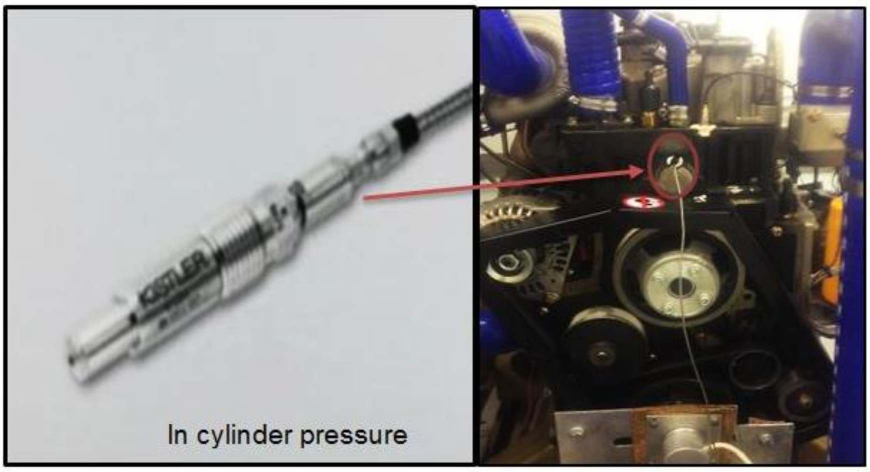


Figure 6-7 In-cylinder pressure sensors

6.3 Vibration Measurements

6.3.1 Engine Cylinder Head Vibration Sensor

For measuring the vibration of the engine body, a piezoelectric accelerometer (model CA-YD-104T) with output sensitivity 0.518mv/m/s^2 was attached to the outer surface of the engine cylinder head; see Figure 6-8 which shows the installation and position of the accelerometer on the cylinder head.

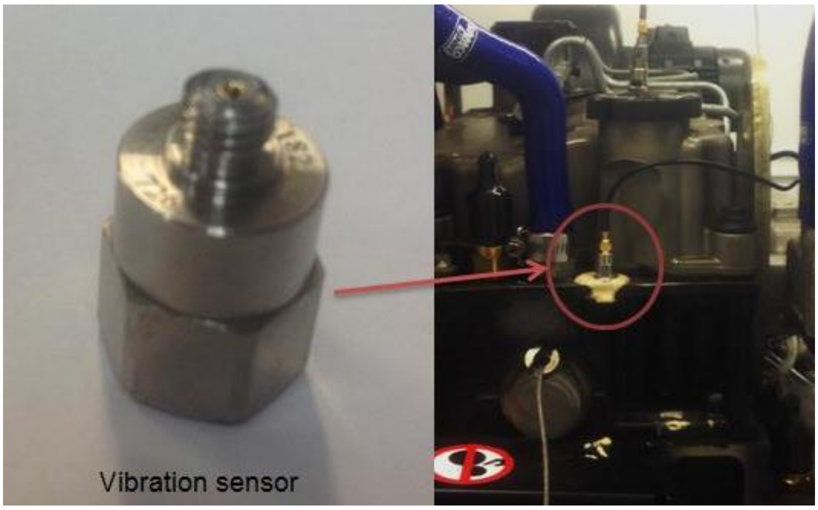


Figure 6-8 Engine cylinder head vibration sensor

6.3.2 Fuel Injection Pump Vibration Sensor

To monitor the vibration of the fuel injection pump, related to the fuel injection pressure, the same accelerometer model (CA-YD-104T) was used. The sensitivity of accelerometer was

4.887mv/m/s^2. Figure 6-9 shows the installation and position of the accelerometer on the surface of the fuel injection pump close to the first injection fuel delivery valve.

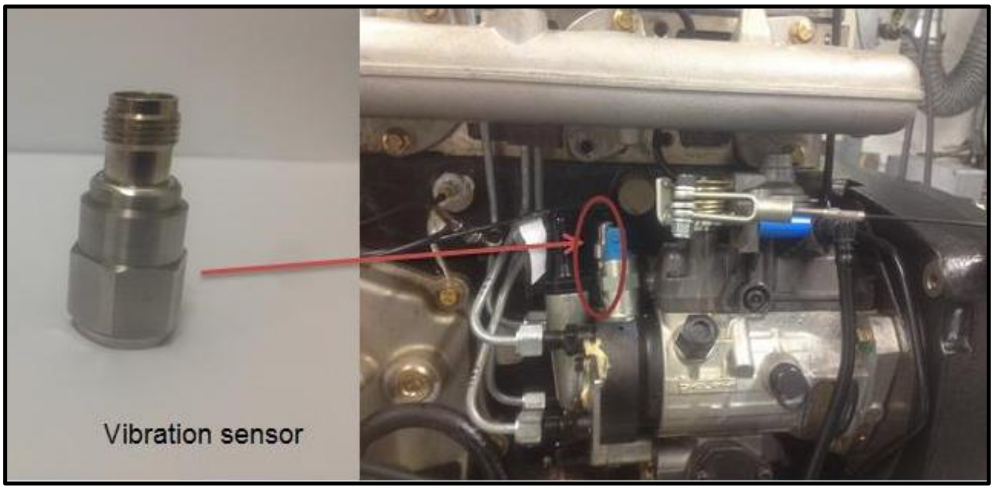


Figure 6-9 Engine fuel injection pump vibration sensors

6.3.3 Optical Encoder

To measure the rotational speed of the crank shaft an incremental optical encoder, serial no: 260-3831 was connected to the front of the crankshaft as shown in Figure 6-10, to measure its angular position. The encoder consisted of a rotating disk, a light source and a photo detector. Because the encoder gave a pulse for every complete revolution of the crankshaft, it allowed time domain averaging to be performed. The optical encoder also provided a reference point which allows each set of data collected to begin at exactly the same crank angle position.

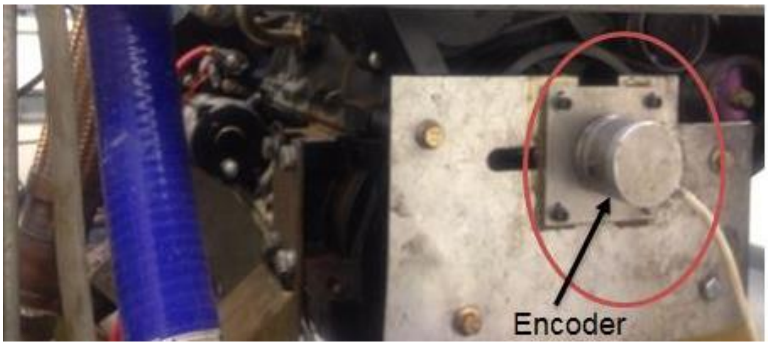


Figure 6-10 Optical encoders position

6.3.4 Charge Amplifier

Three charge amplifier (YE5856, 120CA and Bruel& Kjaer 2635) as shown in Figure 6-11. These were used to amplify the weak signal outputs from the accelerometers and pressure sensors. They produce a voltage output proportional to the change in input charge and the output signal level can be adjusted to best match the various input requirement of voltmeters and analyses.

Figure 6-11 Charge amplifier set to collecting data

6.4 Engine Operation Parameter Measurements

6.4.1 Temperature Measurement

The exhaust, cooling system, oil lubrication, turbocharger, and inlet temperature were all measured and monitored. These temperatures were processed by the CADET V14 software for engine monitoring purposes. The exhaust temperature alone was processed using the Data Acquisition System CED 1401 Power**.** The temperature was measured using PRT K type Chomel-Alumel thermocouples probes.

6.4.2 Air Flow

The air-consumption of the diesel engine was measured using a standard BOSCH-HFM5 hot-film air-mass meter, No. 0280217123. The basic principle of this method is that the heated sensor element in the air-mass meter loses heat to the incoming air. The greater the airflow the more heat is lost. The resulting temperature differential is a measure of the air mass flowing past the sensor. An electronic hybrid circuit was used to condition the signals so that the air-flow quantity could be measured precisely. The air mass flow meter is shown in Figure 6-12.

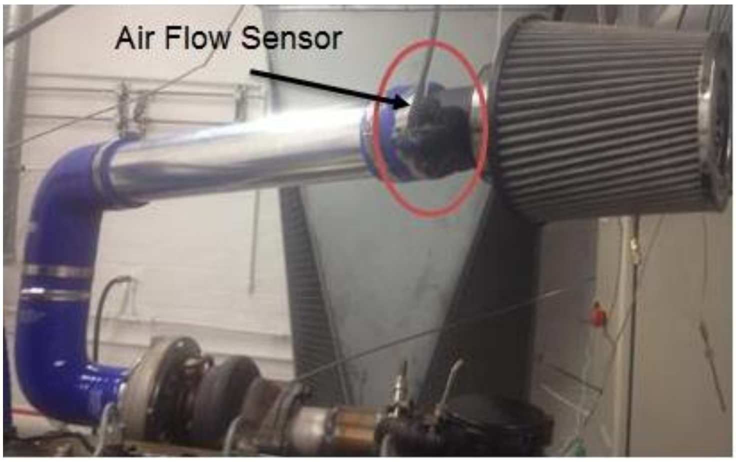


Figure 6-12 Air flow rate sensors

6.4.3 Dynamic Data Acquisition Systems

All the signals collected from the test rig needed to be converted from an original analogue form to a digital form. This has been achieved by using a 16 channel CED 1401 Power 1401 Analogue to Digital Converter (ADC) interface between the transducers and the computer. This data acquisition system was used for converting the signal of in-cylinder pressure, engine encoder (engine speed), air flow rate and engine temperatures shows in Figure 6-13. The data acquisition software is based on a Windows operating system and has the ability to perform on-line data sampling and recording. The software package has a separate set up page for each channel, but will display all signals on one page as presented in Figure 6-13 (b).

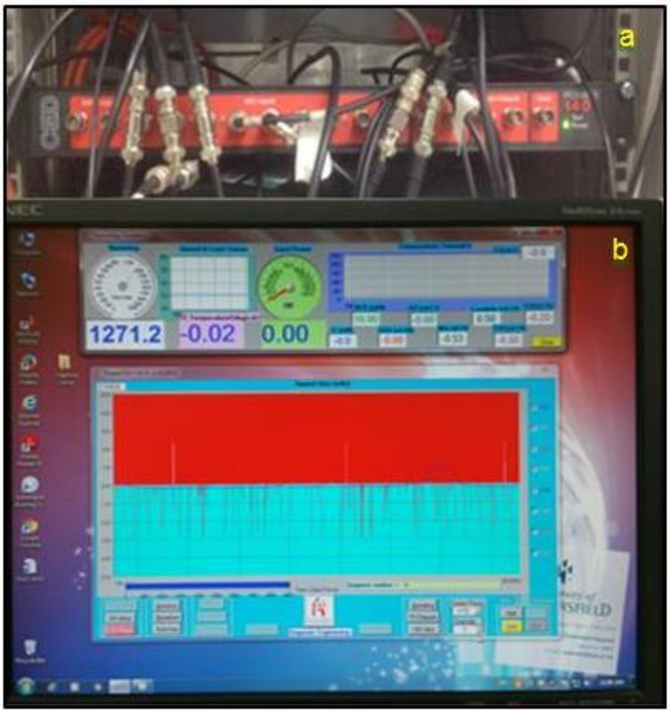


Figure 6-13 Data acquisition system CED 1401

6.4.3.1 Data Acquisition System YE6232B

The data acquisition system is based on a Sinocera Model YE6261B dynamic data acquisition unit with 32 analogue input channels, each channel with 16 bit resolution, synchronized acquisition at 48 kHz per channel, an IEEE 1394 interface, and selectable signal conditioners as can be seen in Figure 6-14. The data acquisition software is based on a Windows operating system and has the ability to perform on line data sampling and recording. The software package has a separate set up page for each channel with a separate signal for each channel as presented in Figure 6-14 (b).

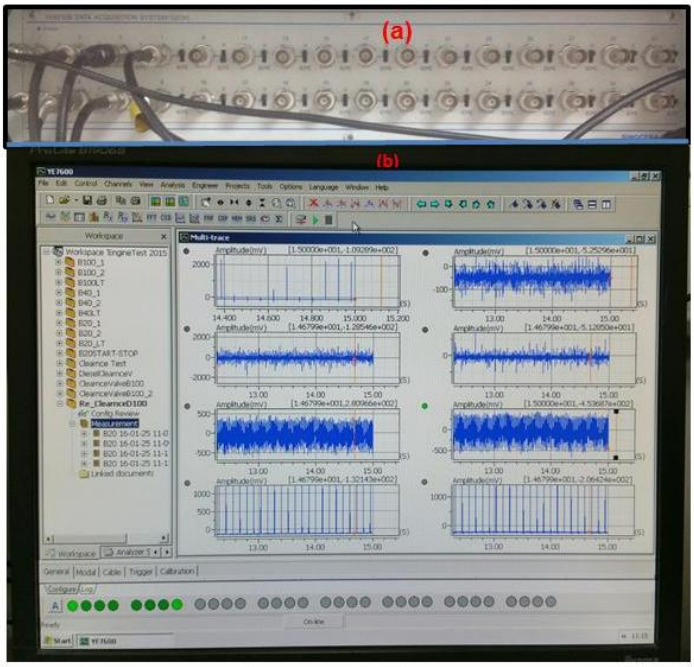


Figure 6-14 Data acquisition system model YE6261B

6.4.3.2 CADET V 14 Test Automation System

The CADET V 14 control system, see Figure 6-15. a software package that provides full control and data logging capability for engine and vehicle testing CADET V 14 has a 1000 channel data logging capacity, multi-screen user interface, on-line editing of tests, calibration procedures, PID channels, drag and drop user display creation, see Figure 6-15**Error! Reference source not found.**. The range of applications includes emissions, fuel consumption and performance testing.

Figure 6-15 Engine control system pages and channels

6.5 Fuel Properties Measurements

In this research study, petro-diesel and three different proportions of biodiesel blends have been tested: in percentage volumetric fraction these were respectively, 0%, 20%, 40%, and 100%, (blends B0, B20, B40, and B100 respectively). The waste cooking oil as biodiesel was produced by a local fuel supplier.

6.5.1 Test Procedure of Fuel Density Measurement

To measure the fuel density, standard procedures as described in BS EN 3675, were followed [191]. A glass hydrometer with a range of specific gravities from 0.700 to 1.000, with an accuracy of three decimal places was used. To collect temperature dependent data, a 100ml graduated cylinder containing the biodiesel sample was placed in a temperature controlled bath. The bath water temperature was varied from room temperature to 95^{0}C. The test was repeated twice for each fuel and the average taken as the representative value. In addition to the hydrometer measurements, the mass/volume method for density measurement was used for comparison.

6.5.2 Test Procedure of Fuel Viscosity Measurement

To measure the fuel viscosity, standard procedures as described in European EN ISO 3104:1996 [192] were followed. This method is commonly used to measure the viscosity of liquid petroleum products. In this research, the Brookfield RV-II viscometer available in Chemical Science at Huddersfield University was used to measure the viscosities for blends B0, B20, B40 and B100. The measurement principle relies on the measurement of the torque necessary to overcome viscous resistance to the movement induced when the sensing element (spindle) is rotating in the test fluid. Fuel properties can be measured over a temperature range from 0^0C to 200^0C [79]. Figure 6-16 shows a schematic of the Brookfield viscometer. Dynamic viscosity (mPa·s) is the resistance to fluid under an applied force. In this work, the dynamic viscosity change with both fuel temperature and proportion of biodiesel present so the spindle speed and shear rates had to be adjusted correspondingly. This instrument was used to obtain absolute kinematic viscosity (mm/s^2), defined as the ratio of the dynamic viscosity of a fluid to its density and calculated using Equation (6-1) equation (6-1) [79].

$$cSt = cP/\rho \qquad (6\text{-}1)$$

Where *cSt* is the kinematic viscosity, *cP* is the dynamic viscosity and ρ, is the fuel density.

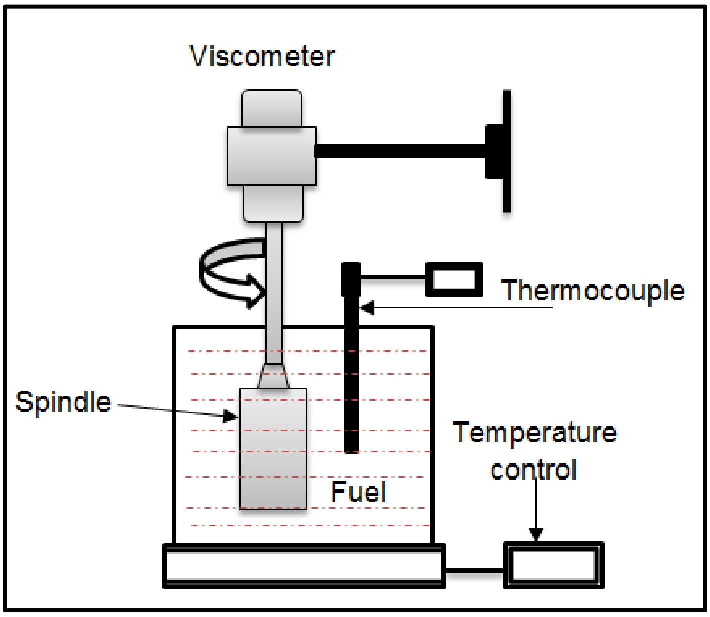


Figure 6-16 Schematic of experimental apparatus Brookfield viscometer

6.5.3 Test Procedure for Measurement of Heat Value

A Parr Adiabatic Oxygen Bomb Calorimeter in Chemical Science at Huddersfield University was used to determine the heating value of petro-diesel, B20, B40 and B100. The auxiliary equipment included a controlled temperature reservoir and automatic pipette for dispensing repeatable 2000 ml of distilled water at a pre-set temperature into a stainless-steel bucket, digital thermometer and ignition switch. The water heater maintained and delivered hot water at a controlled temperature that can be allowing adjustment of the calorimeter jacket temperature. The water cooler provided a uniform supply of cooled water for adjusting the jacket temperature. The important components of the calorimeter bomb are exposed in Figure 6-17.

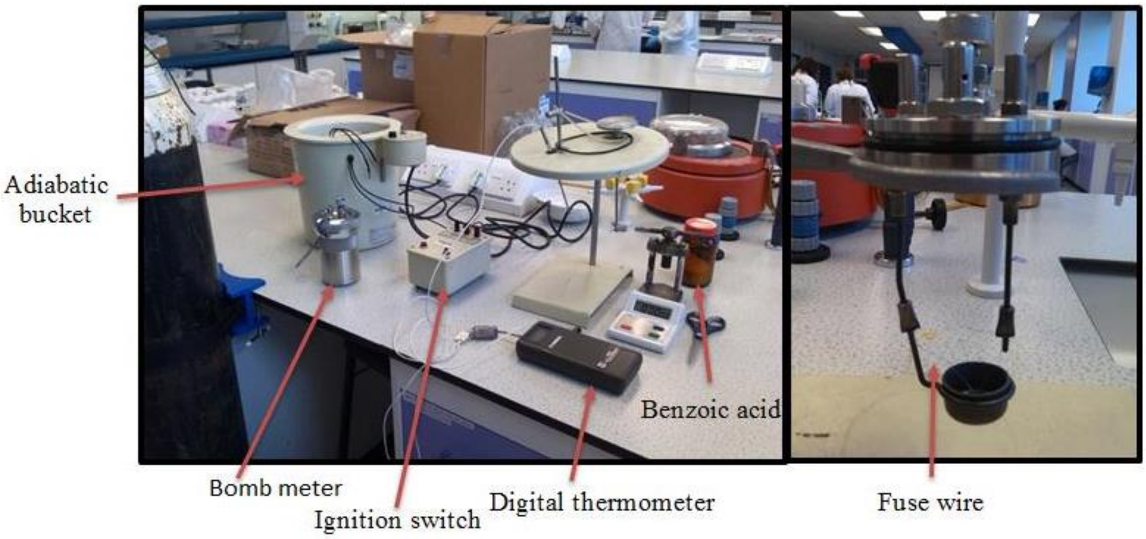


Figure 6-17 Bomb calorimeters for tested heating valve of fuels

6.6 Test Procedures

With the instruments and sensors in place the engine test rig was fully instrumented for measurement of in-cylinder pressure, fuel injection pressure and vibration measurement as shown in Figure 6-18. These measurements allow monitoring of the fuel injection system and engine combustion process and to diagnose the effects of biodiesel include valve clearance faults.

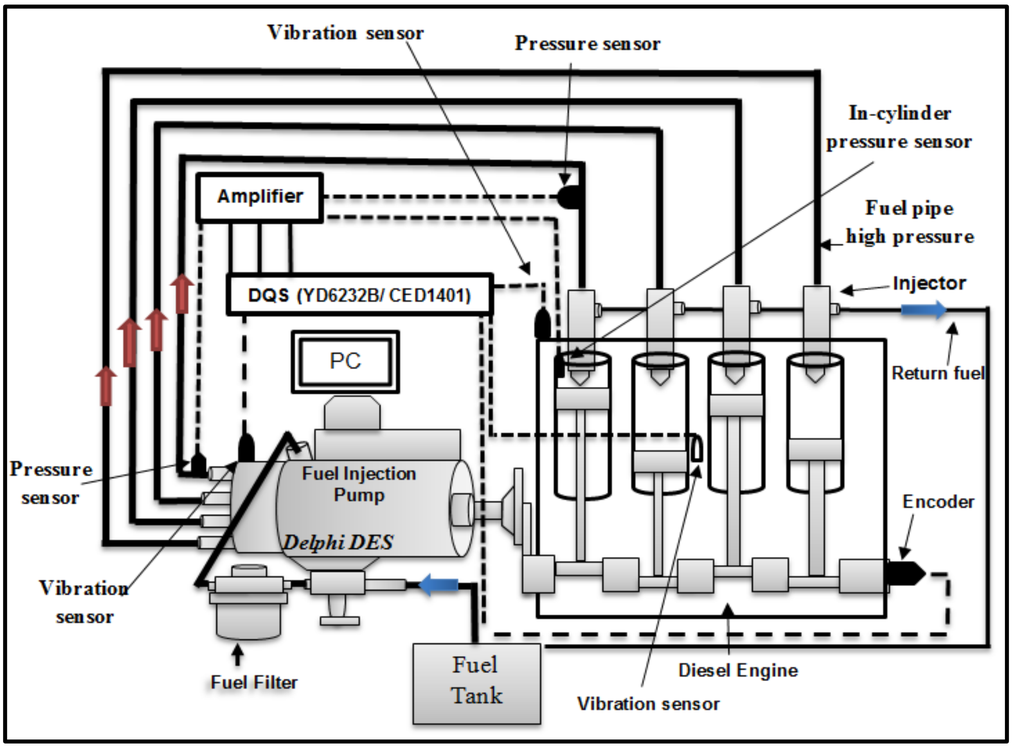


Figure 6-18 Schematic diagram of test rig engine collecting data

6.6.1 Fuel Preparation Test

The biodiesel and petro-diesel were obtained from local fuel suppliers. Separate tanks were, of course, used for petro-diesel and biodiesel. Based on the blend fraction required, the relative volumes of biodiesel and petro-diesel were calculated. For example, to prepare 10 litres of biodiesel blend, B40, 40% biodiesel (4litres) and 60% diesel (6 litres) were used. Figure 6-19 shows samples of the biodiesel blends.

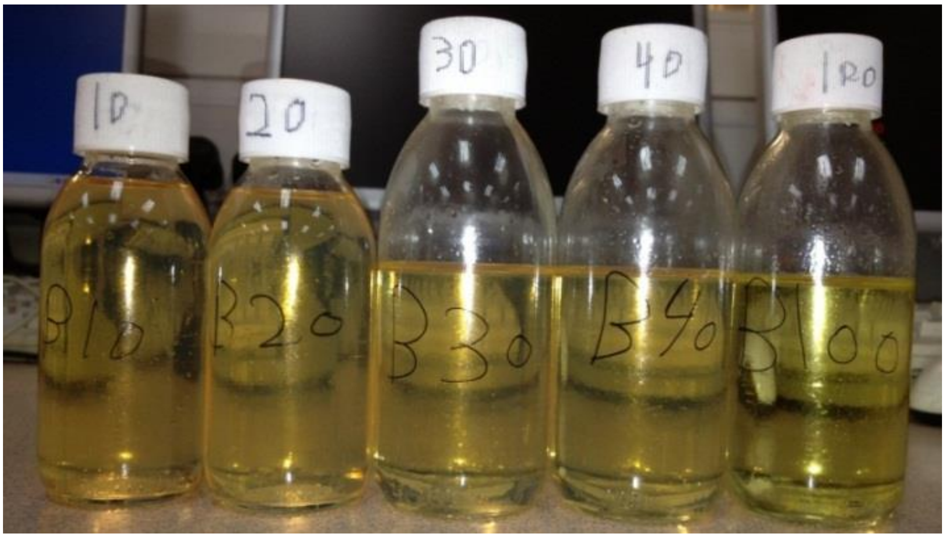


Figure 6-19 Biodiesel and biodiesel blends prepared at the laboratory

6.6.2 Engine Test Operation

A series of tests with different torques were designed according to engine manufacturers' guidelines as observed in Table 6-5. The engine test parameters were as given in Figure 6-20. The engine power and torque curve is presented in Appendix. Based on the engine running at a constant speed and load, measurements were made to evaluate the performance characteristics when using petro-diesel or a biodiesel blend as fuel. The engine speed and load were controlled via the programme CADET V14. The fuel enters to the fuel injection system with temperature 20^0C.

Table 6-5 Engine test parameters on steady operation

Fuel type	Speed rpm	Load N/m
Diesel, B20, B40, B100	1000	0/105/210/315
Diesel, B20, B40, B100	1300	0/105/210/315/420
Diesel, B20, B40, B100	1600	0/105/210/315

6.6.3 Test Procedure for Varying Valve Clearances

The inlet and exhaust valves are important engine components and, because they repeatedly impact on the cylinder head, are major excitation sources. In this research, clearance valves have been studied as major source of faults in a diesel engine. The engine has two inlet and two exhaust valves in each cylinder, see Figure 6-20. As the camshaft rotates, see Figure 6-21 the cam lobe moves up, exerting an upward thrust which causes the tappet to rotate pushing against the valve stem or pushrod. This thrust overcomes the valve spring pressure as well as any gas pressure acting to reseat the valve.

For each engine cycle, the crankshaft makes two turns, whereas the camshaft makes a single rotation. The angular positioning of the cam lobes on the shaft and the valve spring forces determines the sequence of opening and closing of valves. The design of the lobes determines how high the valve opens (maximum valve lift) and how long it will remain open (opening period).

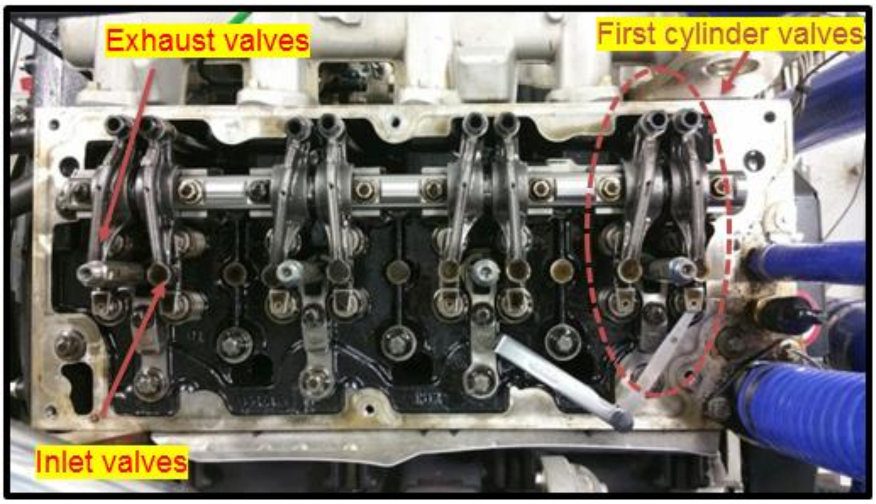


Figure 6-20 Engine valves of inlet and exhaust

However, there is always some clearance between the valve and the cam in order to limit the seating velocities and sudden acceleration of the valve train components and it is necessary to provide appropriate opening and closing ramps. This research investigated clearance faults in both inlet and exhaust valves, tested separately. Table 6-6 shows the permitted ranges of valve clearance for both inlet and outlet valves and also shows the abnormal valve clearances seeded into the system.

Table 6-6 Engine clearance valve range

Engine Valves	Manufacturer range	Abnormal clearance on Cyl. (1)	Change (%)	Fuel
Inlet valve	0.35mm	0.42 mm	20	Diesel/B20/B40/B100
Exhaust valve	0.56 to 0.64 mm	0.76 mm	18.75	Diesel/B20/B40/B100

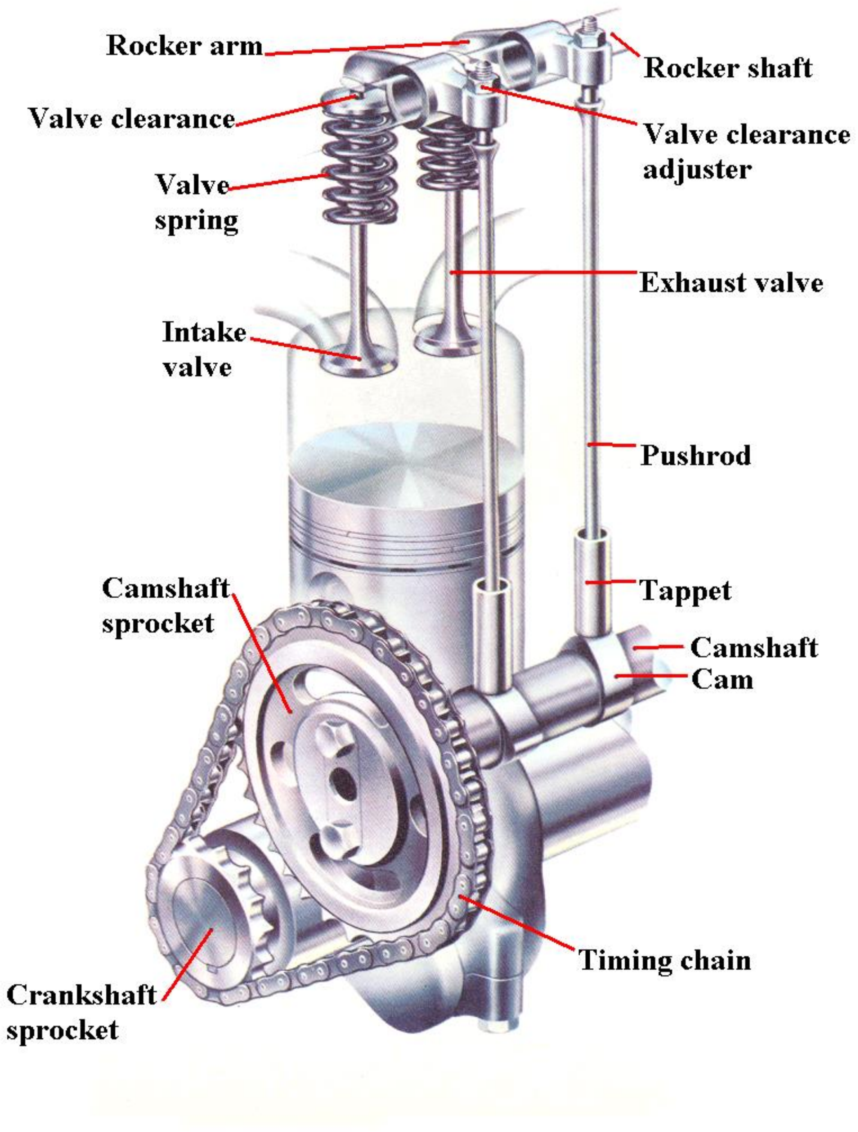


Figure 6-21 Schematic of engine inlet and exhaust valve trains [193]

6.7 Summary

This chapter focused of the information and description of the facilities experimental which is required for biodiesel characterisation. Diesel engine test characteristics with specifications and measuring instrumentation were evaluated to be able to meet the requirements for this study. The specifications of experimental measurement system such as data acquisition system and application software have been presented.

Moreover, the test procedures of the physical properties of biodiesel and biodiesel blends have been elaborated based on the European biodiesel test standards. In the procedures test section, the methodology of biodiesel blending, fuel injection procedures and valves train clearance condition have been discussed.

CHAPTER SEVEN

7 INVESTIGATION INTO THE EFFECTS OF BIODIESEL FUELS ON FUEL INJECTION USING PUMP VIBRATION

This chapter presents the effects on the diesel engine fuel injection system and combustion process of using four biodiesel blends (B0 petro-diesel, B20, B40 and B100), which is achieved by taking the diesel (B0) as the baseline.

The intrusive measurements of fuel injection pump pressure and fuel injector pressure along with in-cylinder pressures are examined to show the changes in dynamic excitations corresponding, these different fuels under a wide range of engine operation conditions. Then non-intrusive vibrations are analysed to show the correlations with the pressures and effective indications of changes in fuel types.

7.1 Introduction

During fuel injection process, the fuel injection pressure is rising in few second to inject the fuel into the combustion chamber. A consequence of the higher pressure of fuel injection pressure is an increase of structural stress on the pump and injector [129]. The sensor of pressure requires an extended measurement capability as well as structural strength beyond the fuel system burst limit. While sufficiently high burst pressure levels can be achieved, meeting lifetime pressure cycling durability is challenging more details in chapter 4.

In particular, the fuel injection structural working under high pressure, that requires extensive pressure cycling testing with limit information and specification of particular focus on parts of pressure and pressure parameters. In this research, fuel injection pressure cycling tested in the first cylinder of a diesel engine at different operations, with biodiesel and biodiesel blends that are due to mounting conditions need to be considered as these can have an important influence on the critical stress levels with different fuel properties.

Moreover, to monitor fuel injection condition in each injection, the vibration techniques can be used to monitor each injection, at different stages of the engine operation with fuelled biodiesel and biodiesel blends as discuss below in this chapter. Also in this chapter the effects of fuel injection on combustion process when engine running with biodiesel are investigated [109]. It details the effects of fuel injection with engine running by biodiesel on engine investigated based on fuel injection pressure and injection parameters, in-cylinder pressure, and vibration response of FIP and cylinder head vibration.

7.2 Fuel Injection Pressure Measurements

As described previously, the fuel injection systems of a diesel engine generates a high pressure to inject the fuel into each cylinder during one rotation of a plunger. However, each part of the fuel injection system has a different pressure.

In this study fuel injection pump (FIP) pressure and fuel injector pressure are investigated, see in Figure 7-1. The waveforms clearly confirm that the injector pressure relative to the FIP pressure is delayed and of greater amplitude. This phenomenon has been observed many times before [187, 188]. It can be seen that FIP pressure and injector pressure increase with both engine load and engine speed.

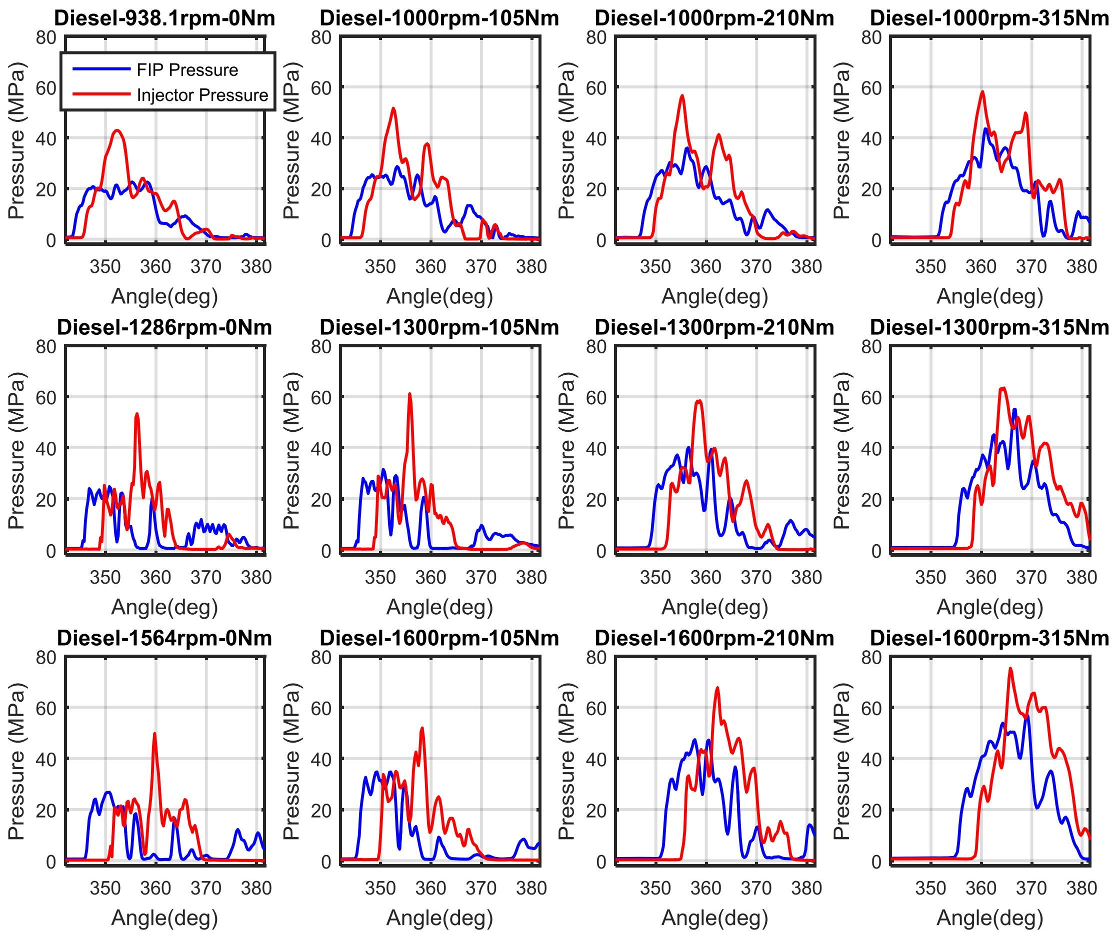


Figure 7-1 Pressure waveforms of the FIP and fuel injector as a function of cam angle for petrodiesel, three different engine speeds and four loads

7.3 Effects of Biodiesel on Fuel Injection Pressure

This section investigates and compares FIP and injection pressure for biodiesel blends B0, B20, B40 and B100. Figure 7-2 shows the measurement FIP pressure waveforms is under different engine operating conditions. As in the previous section it can be seen that the amplitude of duration of FIP pressure increases with both the load and the speed, but it can also be seen that the higher the proportion of biodiesel in the blend the more advanced the fuel injection and the greater the pressure for all engine speeds and loads.

In order to see the changes more accurately, three key fuel injection parameters: maximum pressure, injection timing and injection duration, have been extracted from the waveform. These parameters have been studied and compared for the four biodiesel blends tested.

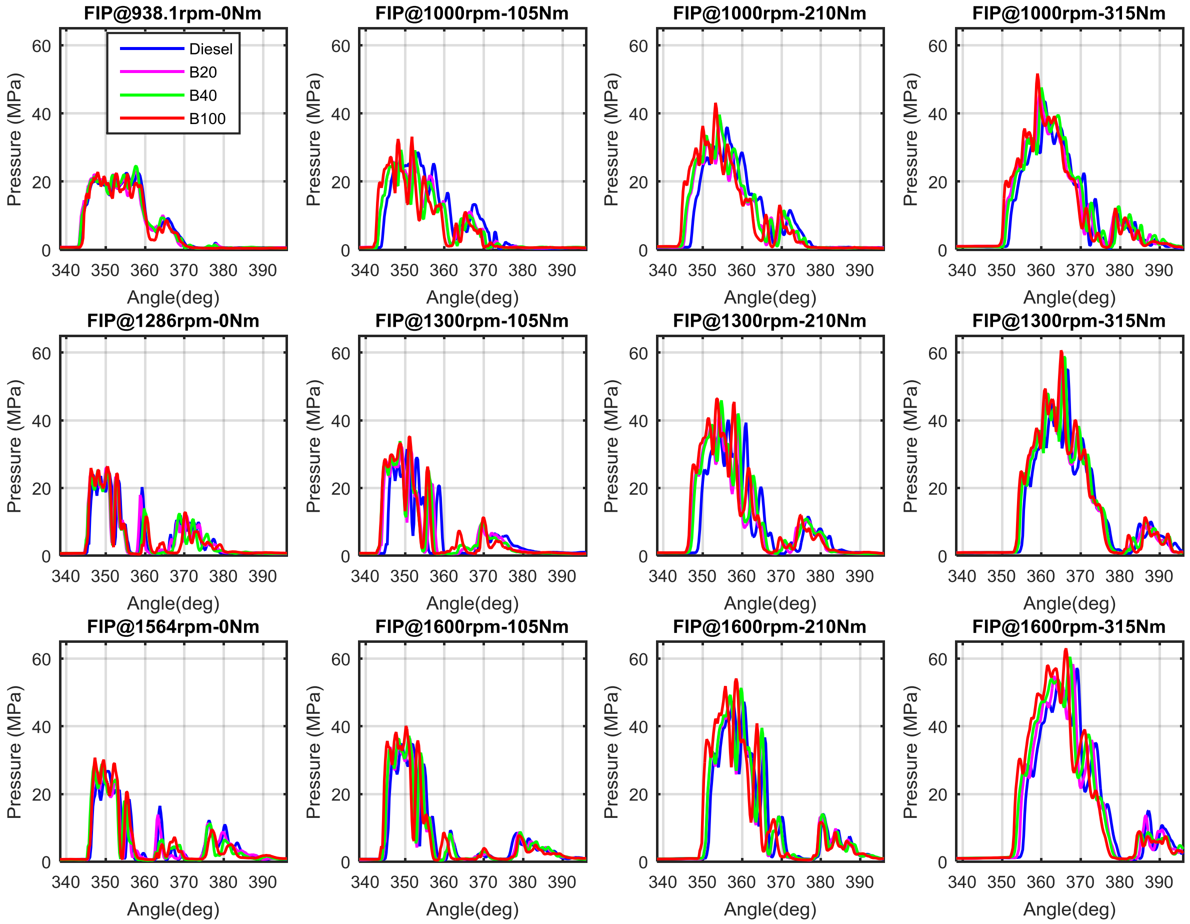


Figure 7-2 FIP pressure waveforms as a function of cam angle for biodiesel blends B0, B20, B40 and B100, for different engine speeds and loads

Figure 7-3 presents a comparison of maximum measured pressure for engine speeds 1000 rpm, 1300 rpm and 1600 rpm, under loads 0, 105 Nm, 210 Nm and 315 Nm. The results clearly show that the peak pressure increases significantly with increased proportion of biodiesel in the blend [13]. This result is explained by the higher viscosity and density of biodiesel compared to the standard petro-diesel (B0). Of course, the more pressure in fuel injection equipment the greater the forces or stresses on fuel injection components such as the gears, valves and pipeline of the injection pump and fuel injector.

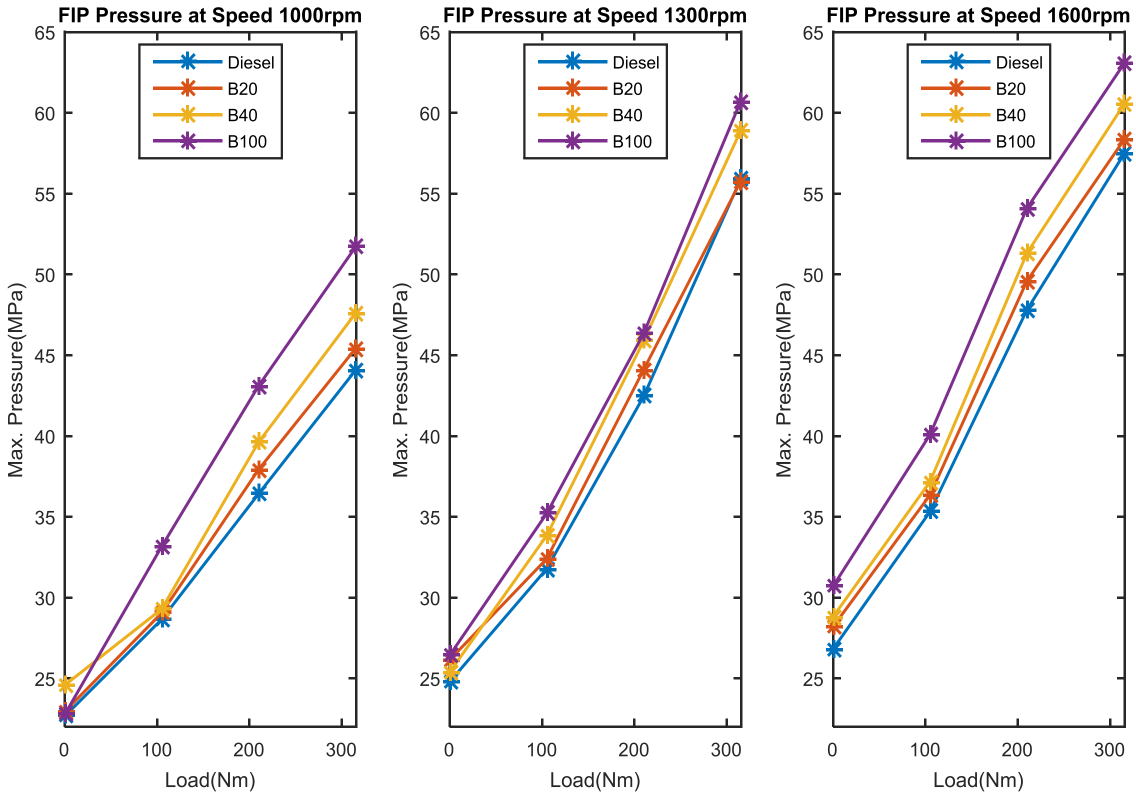


Figure 7-3 Peak FIP pressure for B0, B20, B40 and B100, as a function of load for different engine speeds

Moreover, fuel injection timing or fuel injection start is an important parameter for fuel injection systems, which eventually affects both engine performance and emission characteristics [194, 195]. The proportion of biodiesel in the fuel is expected to influence fuel injection start and the injection strategy [20, 196, 197].

Figure 7-4 presents the start of injection as cam angles (timing) for B0, B20, B40 and B100 biodiesel blends under different engine conditions. As would be expected the plots show the same trends for all four fuels with operating conditions. However, the results also show an advance in injection timing which increases the greater the proportion of biodiesel in the fuel. These results are again attributed to the higher viscosity and density of biodiesel compared to petro-diesel. Advanced injection timing leads to rapid engine combustion hence pressure higher and temperatures[195, 198], which produces rough operation and high NOx emissions.

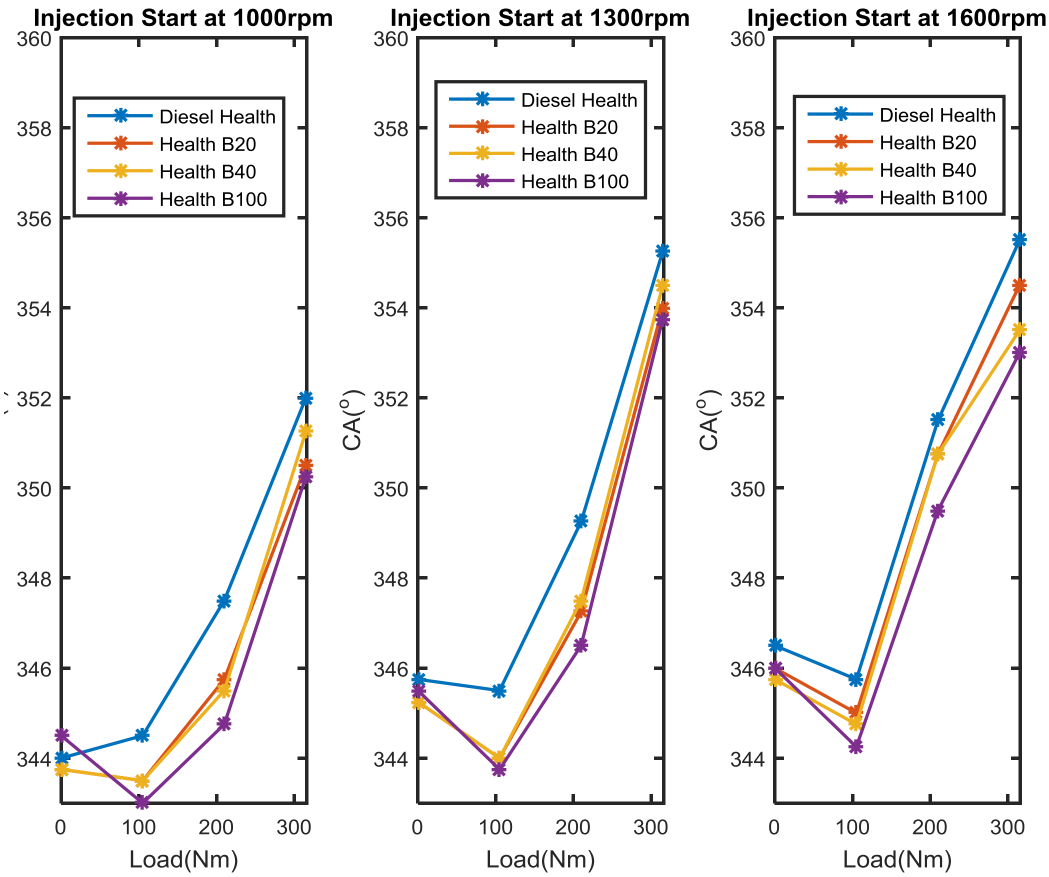


Figure 7-4 Injection start on different engine parameters with crank angle

The fuel injection duration or injected fuel quantity was investigated with the diesel engine fuelled by the four biodiesel blends (B0, B20, B40 and B100) at three engine speeds (1000 rpm, 1300 and 1600 rpm) and four loads (0, 105, 210 and 315 Nm). Figure 7-5 shown the results extracted by the simulated injection rates. It can be seen that no consistent pattern is observed for the proportion of biodiesel in the bled. It is suggested that the reason for this may be due to the nonlinear nature of the fluid dynamic effects. The biodiesel alters the pressure supply characteristics, thereby influencing the fuel injection process and combustion. However, these changes appear not to be as significant as claimed in previous studies. Nevertheless, the increase in the peak pressure indicates a higher dynamic load applied to the pump and supply lines, which may, long term, have detrimental effects on these components.

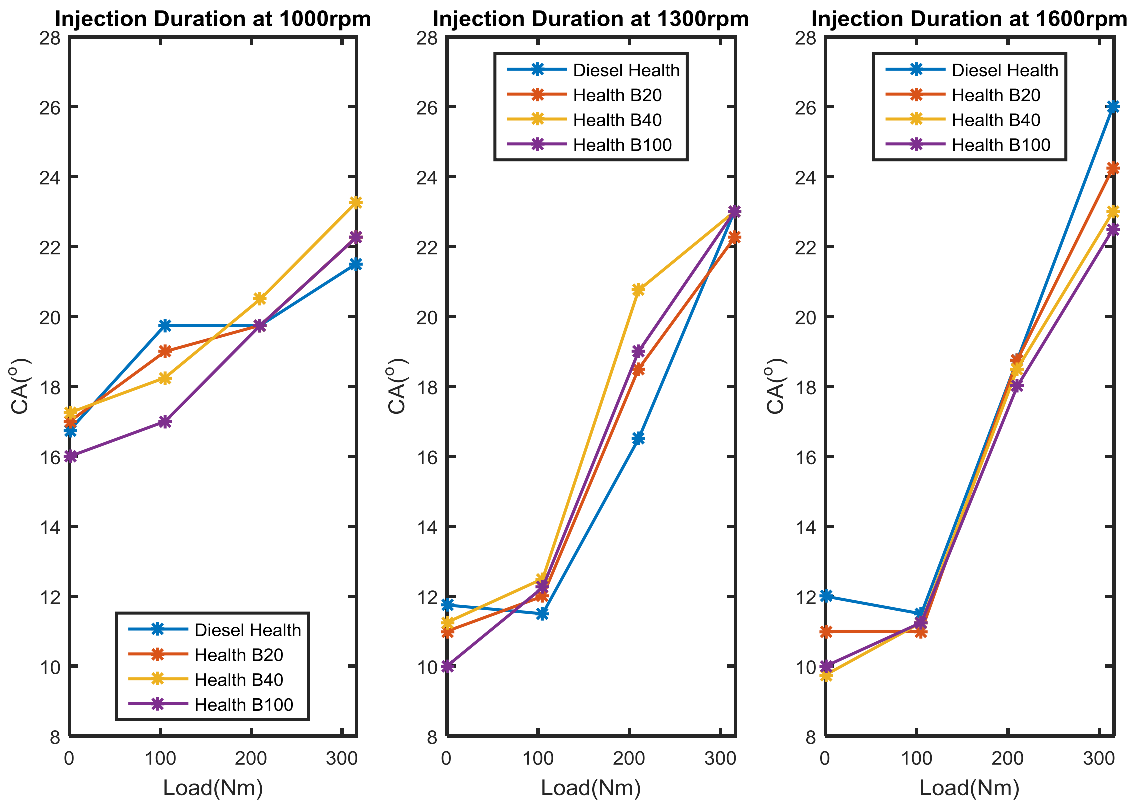


Figure 7-5 Injection duration of engine running on biodiesel blends B20, B40, B100 at 1000, 1300 and 1600 rpm, and subject to four loads

7.4 Effects of Biodiesel Fuel on Fuel Injection: Vibration of the Injection Pump

The high pressure impulses in the fuel injection are associated with the reciprocating forces of the plunger motion and the impacts due to opening and closing of the delivery valve are the main causes of vibrations of the pump housing [17, 199, 200]. To investigate the effects of different biodiesel blends on fuel injection, the vibration of the fuel injection pump was measured. Figure 7-6 presents the vibration signals from the fuel injection pump body with the engine running on biodiesel blends B0, B20, B40 and B100 under different engine speeds under a load of 105Nm. It can be seen that the amplitude of injection pump vibration increases with engine speed for all fuels tested. These results are in good agreement with the results of pressure measurement as discussed in section (7-1).

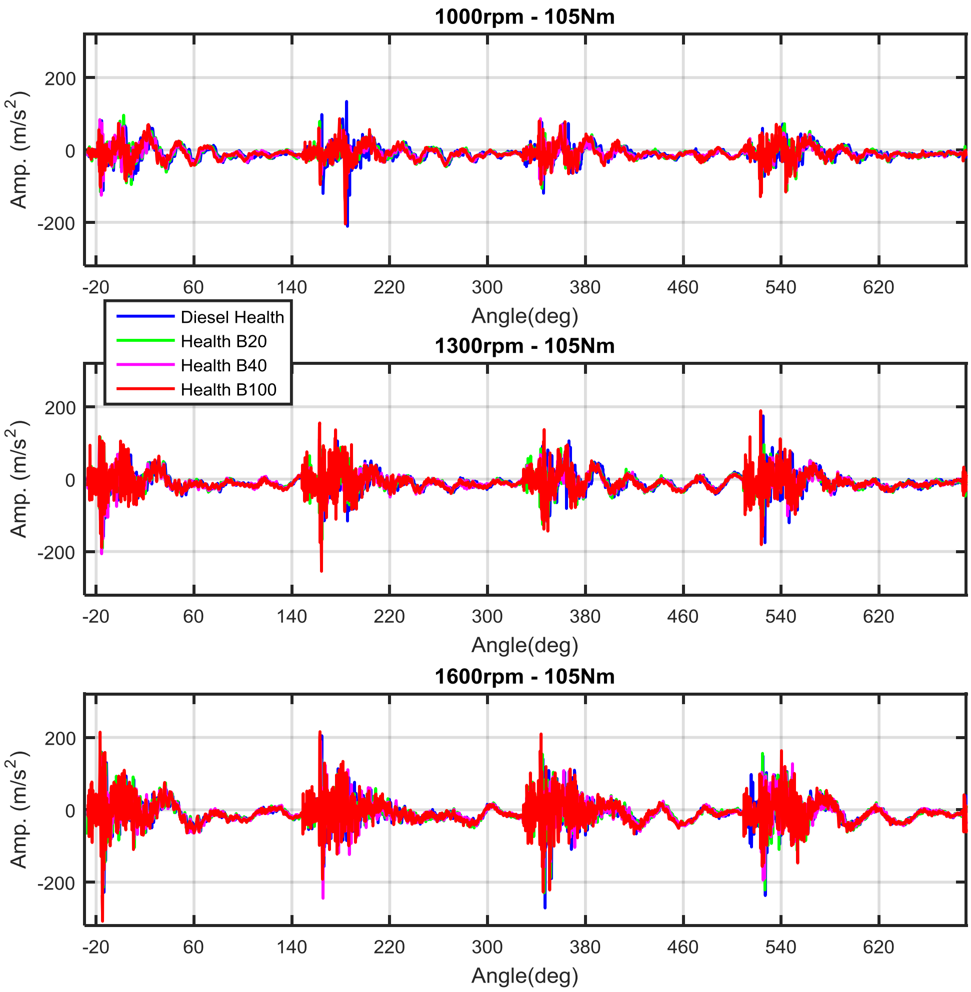


Figure 7-6 Vibration of fuel injection pump as a function of crank angle with engine running on biodiesel blends B0, B20, B40 and B100 for three engine speeds

However, Figure 7-7 shows the fuel injection pump vibration signals for an engine speed of 1000 rpm and load of 210 Nm, for biodiesel blends B0, B20, B40 and B100. The results confirm that the vibration signal is closely correlated with the pressure variations. The initial rise in vibration level appears to correspond to the initial increase in pressure in the FIP. Of note, are the two clusters of transient responses, which is correspond to the two impacts caused by the opening and closing of the delivery injection fuel valve and needle injector valve. The fuel delivery valve and needle injector valve operate at nearly the same time [131].

Secondly, the amplitudes of the transient responses increase consistently with pressure amplitude. These vibrations could be used to indicate the amplitude of the high pressure fuel injection pump. To gain a better understanding of the vibration, the signals of time domain are analysed using frequency domain. It was found that there is clear, low frequency transient responses between two high frequency transients and their amplitude increase with pressure, these low frequency transients mainly come from the reciprocating forces due to the plunger, cam ring motions and associated transmissions. Vibration frequency analysis has been used with complex mechanical processes such as the fuel injection systems of diesel engines [129, 177, 201, 202].

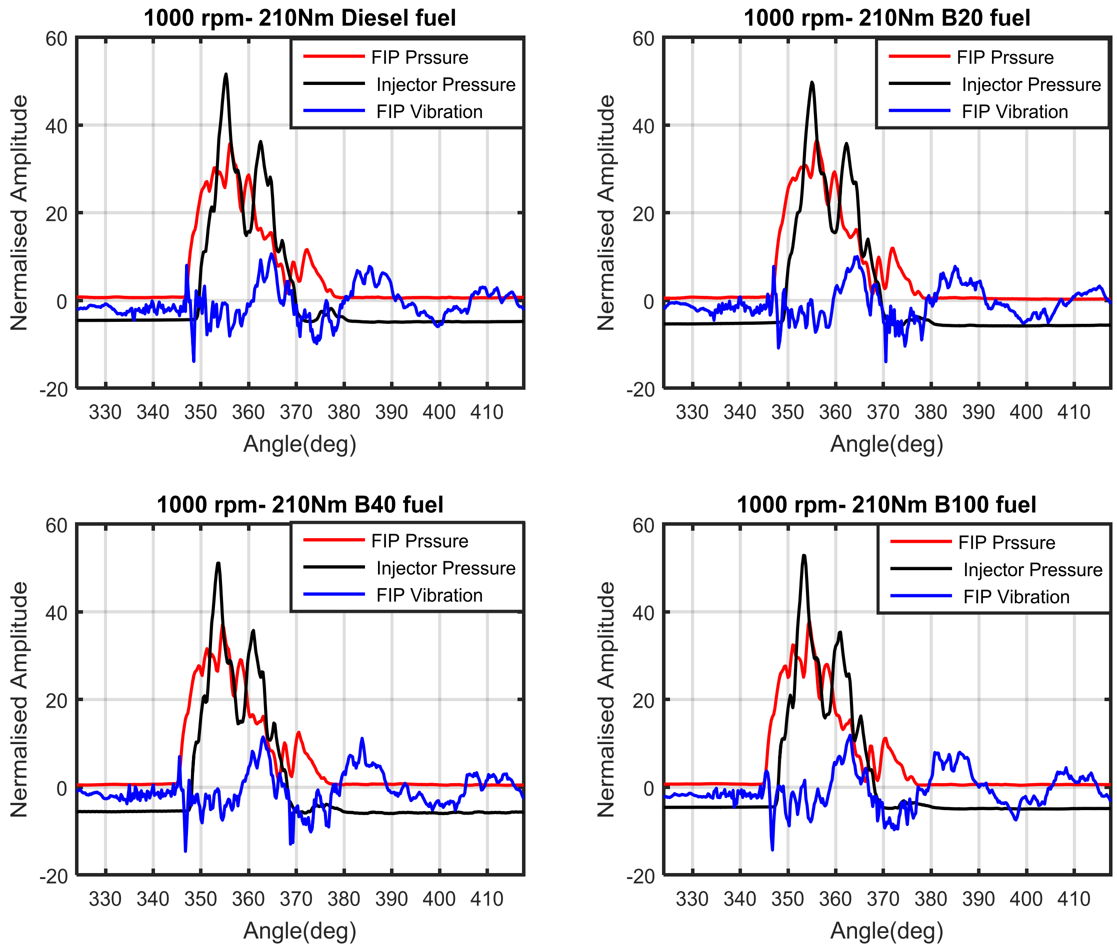


Figure 7-7 FIP vibration levels, FIP pressure and injector pressure as a function of cam angle for biodiesel blends B0, B20, B40 and B100 at load of 210 Nm

Figure 7-8 (a) shows typical FIP vibration spectra for two different loads at constant engine speed of 1600 rpm. It shows that there are strings of harmonics in the spectrum due to the injection frequency which are calculated using Equation (7-1).

$$f_i = \frac{n}{2 \times 60} \times 4 \qquad (7\text{-}1)$$

, where n is the engine speed in rpm. The spectral characteristics show high correlations of vibration with the dynamic loads produced by the periodic intermittent fuel injections.

The figure clearly shows that peak amplitudes of frequency increase with load. These discrete components mainly relate to the reciprocating excitation of rotary with pump plunger under liberation of fuel, and their amplitude may be an effective indicator of the interaction between the mechanical motion and the flow of the fuel.

Moreover, the spectrum also shows distinctive continuous contents in the high frequency range that also increase with load. As these contents relate more to the impulsive responses due to the impacts of the delivery valve, it may be possible to use them for evaluating valve motion. Moreover, the spectra for the two biodiesel blends and biodiesel are shown in Figure 7-8 (b, c) show clear differences. The content of the spectrum for B100 at the injection frequency and higher order harmonics show visible increases relative to petro-diesel due to the higher resistive loads caused by the higher viscosity and greater density of the biodiesel. The continuous content also exhibits an increase for similar reasons. These changes are much smaller compared to those obtained due to a change in engine load but are very similar. This indicates that increasing load and increasing density and viscosity have much the same effect on fuel injection pump pressure dynamics. Thus, for constant load, the spectrum changes could be used to evaluate fuel quality.

As discussed above, there are two main sources of fuel injection pump vibration which show up in different frequency ranges. The frequency content below 400 Hz represent the effects of interactions due to reciprocating forces, whereas the frequency content between 400 Hz and 2,000 Hz is largely due to mechanical impacts of the delivery valves and dynamic fuel variation from fuel injector needle valve.

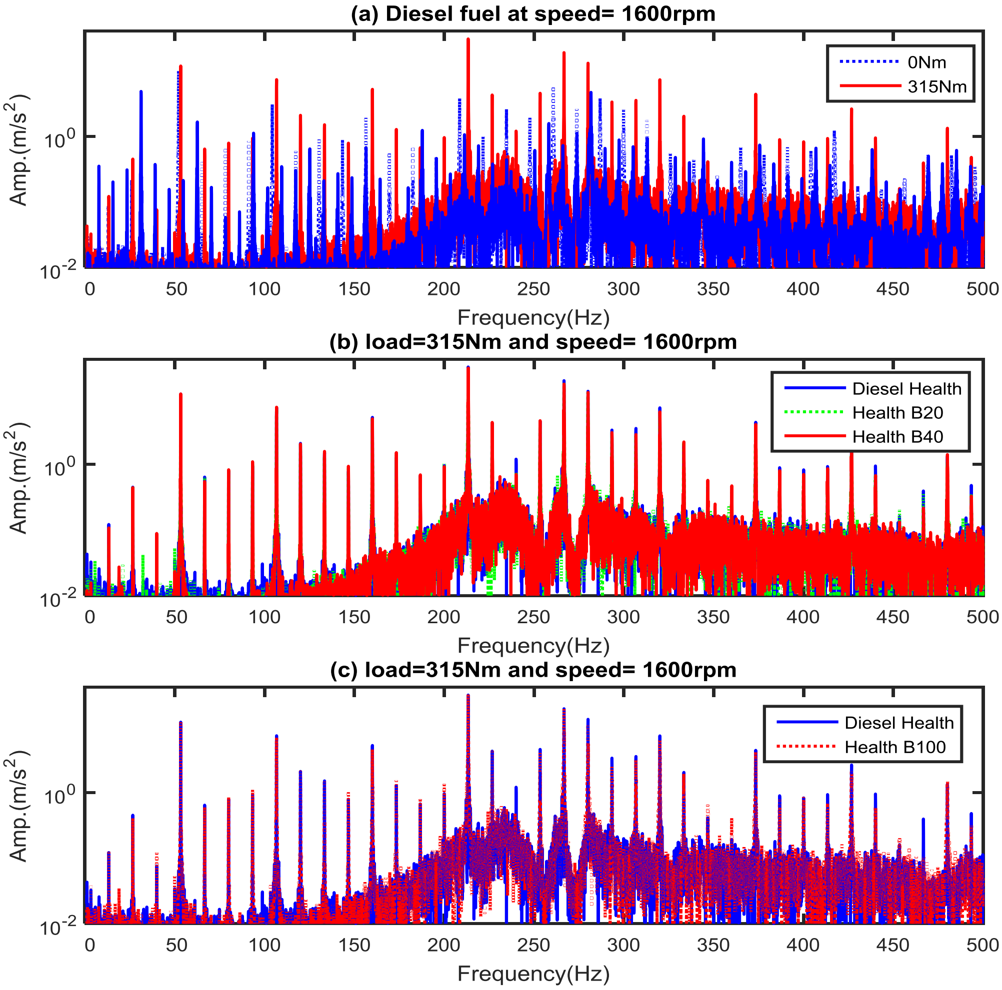


Figure 7-8 FIP vibration spectra for engine speed 1600 rpm: (a) for petro-diesel at two different loads (b) for biodiesel blends B0, B20 and B40, and (c) for biodiesel blends B0 and B100

Figure 7-9 shows the average amplitude of the FIP vibrations over two frequency ranges from DC to 400 Hz and 400 Hz – 2k Hz, referenced as low and high frequency range respectively, at engine speeds of 1000, 1300 and 1600 rpm, and loads of 0, 105, 210 and 315 Nm, when using biodiesel blends B0, B20, B40 and B100. It can be seen from Figure 7-9 that for all three engine speeds and all biodiesel blends, the amplitude of both the low and high frequency content increased with load.

Generally the vibration levels, for both high and low frequency bands, for B100 are greater than for petro-diesel, and show a slightly steeper rate of increase with increase in load. This is attributed to the additional load caused by the higher viscosity and density of biodiesel. However, at low loads and lowest speed, see Figure 7-9 (a) the effects of greater viscosity and density are not so pronounced and there is some overlapping of the plots.

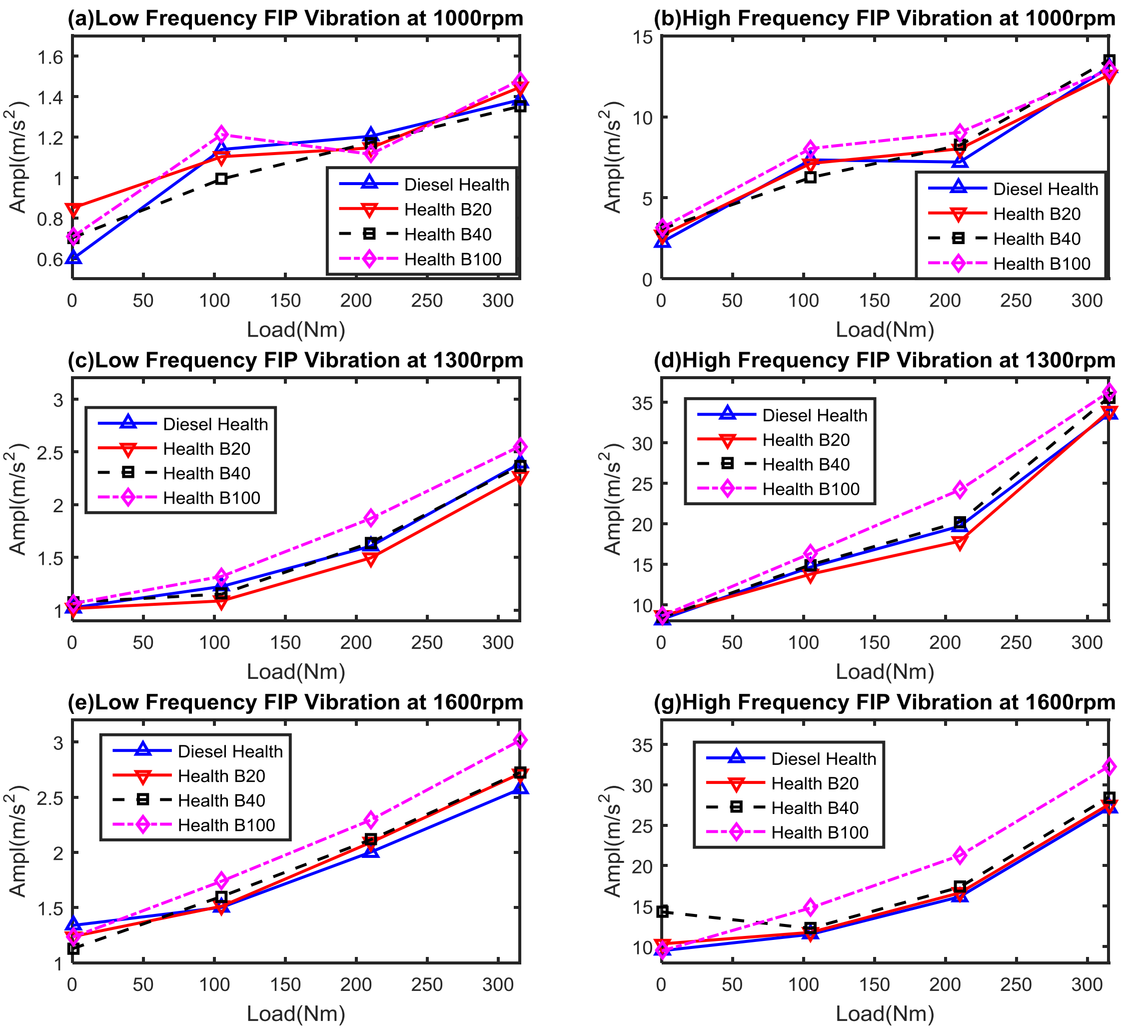


Figure 7-9 Amplitudes of low and high frequency bands for vibration measured on the FIP as a function of load, for biodiesel blends B0, B20, B40 and B100, at three engine speeds

However, further consideration of Figure 7-9 (b, d, and g) shows that the biodiesel blends B20 and B40 consistently produce vibrations that are not significantly different from those produced by petro-diesel. This suggests that the properties of fuel blends might be adapted to reduce impact excitation and help maintain the contact surfaces of the delivery valve, and possibly the nozzle valve in the injector, in a good condition. With its higher viscosity and density, biodiesel fuel requires more power to drive the plunger and hence there is more dynamic loading on the system. This resulting of vibration fuel injection pump with frequency range dynamic behaviour almost is much closing with the resulting of fuel injection pump pressure measurements.

7.5 Effects of Biodiesel Fuel Blends on Engine Combustion Using In-cylinder Pressure Measurements

This section reports the investigation of and consequently the effects of biodiesel blends with fuel injection on engine combustion process. In-cylinder pressure measurement is considered to be a very valuable source of information during the development and calibration stages of the engine combustion process. The in-cylinder pressure signal can provide vital information such as peak pressure, P-V diagram, mean effective pressure, fuel supply effective pressure, heat release rate, combustion duration, ignition delay and so on [203, 204]. In-cylinder pressure data in this research was used to measure parameters such as in-cylinder peak pressure, pressure rise rate, heat release rate and cumulative heat release.

Figure 7-10 shows the variation of in-cylinder pressure within the combustion chamber of the test engine with crank angle when operating on B0, B20, B40 and B100 diesel blends at engine speeds 1000, 1300 and 1600 rpm and engine loads of 0, 105, 210 and 315 Nm. In all cases the peak in-cylinder pressure of the engine running on B20, B40 and B100 was slightly higher than with petro-diesel. These results effected of biodiesel on fuel injection periphery effect on engine combustion stage. The plots of the combustion chamber pressure show advanced fuel injection, as discussed in Section 7.3. The advanced combustion process is due to the easy flow ability of biodiesel, and its other relevant physical properties such as density and bulk modulus [205, 206].

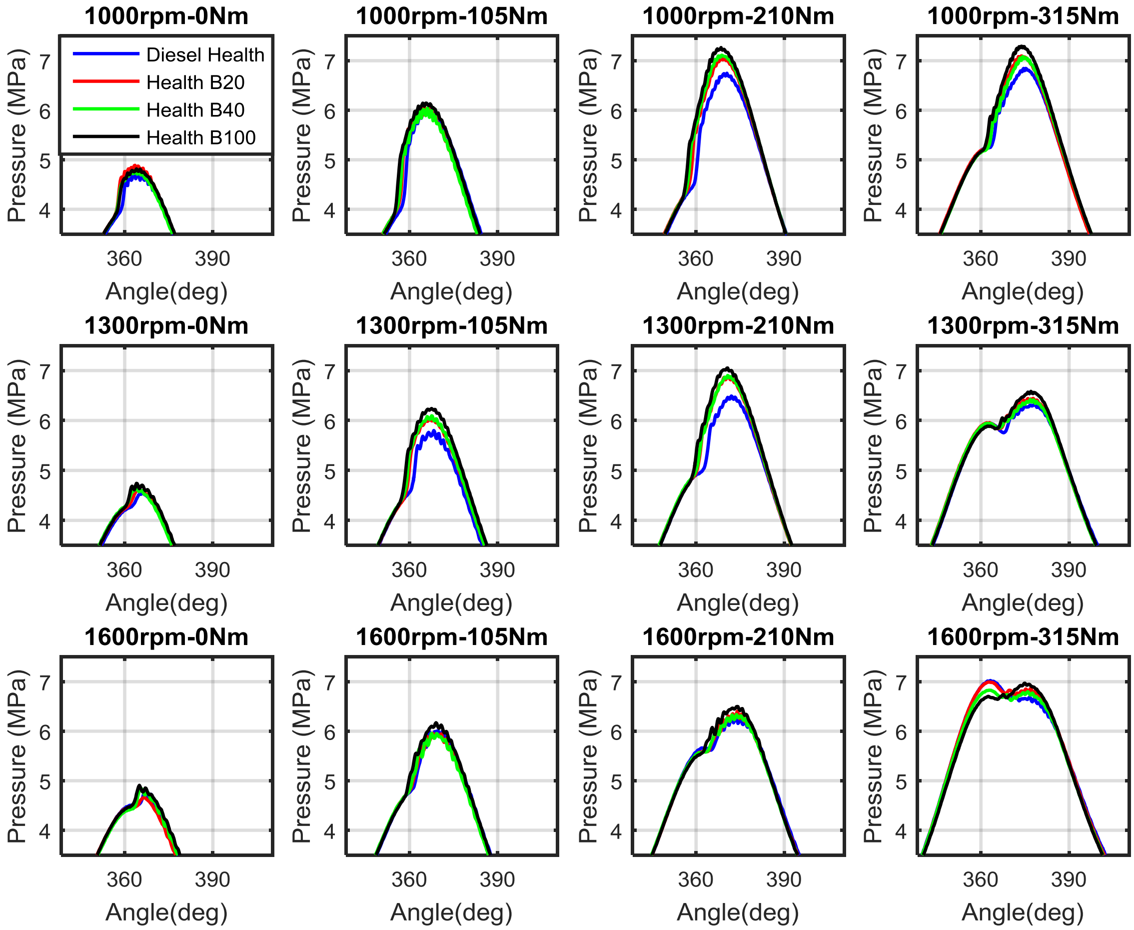


Figure 7-10 In-cylinder pressure as a function of crank angle for engine running with B0, B20, B40 and B100 at three engine speeds and four engine loads

Moreover, Figure 7-11 shows the peak in-cylinder pressure of the engine running on B0, B20, B40, and B100 for engine speeds, 1000, 1300 and 1600 rpm and loads 0, 105, 210 and 315 Nm. It can be seen that, generally, the in-cylinder pressure increased with increasing engine load (though there is an apparent discrepancy at 1300 rpm and 330 Nm). This is due to an increase in air/fuel ratio with engine load increment. It can also be observed that, generally, the peak in-cylinder pressure is higher for biodiesel than for petro-diesel (this is especially true at 1300 rpm) but the differences may not always be significant. These results agree with those previously published[104, 207].

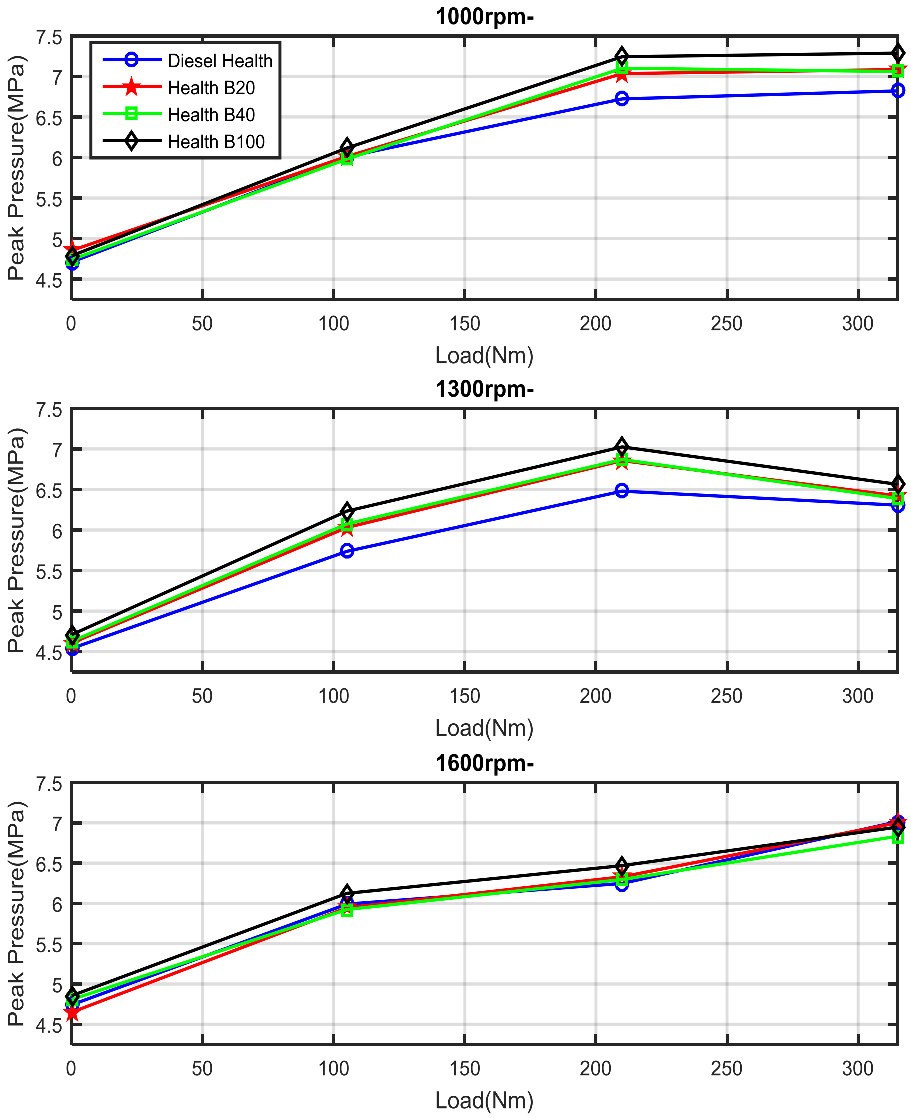


Figure 7-11 In-cylinder peak pressures for engine running with biodiesel blends B0, B20, B40 and B100 for three engine speeds and four loads

The rate of in-cylinder pressure rise with crank angle for biodiesel blends for engine speeds 1000, 1300 and 1600 rpm, and loads of 0, 105, 210 and 315 Nm under steady state operating conditions are shown in Figure 7-12. It can be seen that, for all engine conditions the commencement of the pressure rise for biodiesel is slightly more advanced than for petro-diesel. Also the results show the pressure rise for petro-diesel is slightly greater than for biodiesel. The reason of high pressure at this operating condition is a very small quantity of fuel is injected into the combustion chamber and combustion starts after TDC. The rate of pressure rise is higher for biodiesel at higher engine loads and higher speeds. This is due to the higher rate of heat release during the premixed combustion phase.

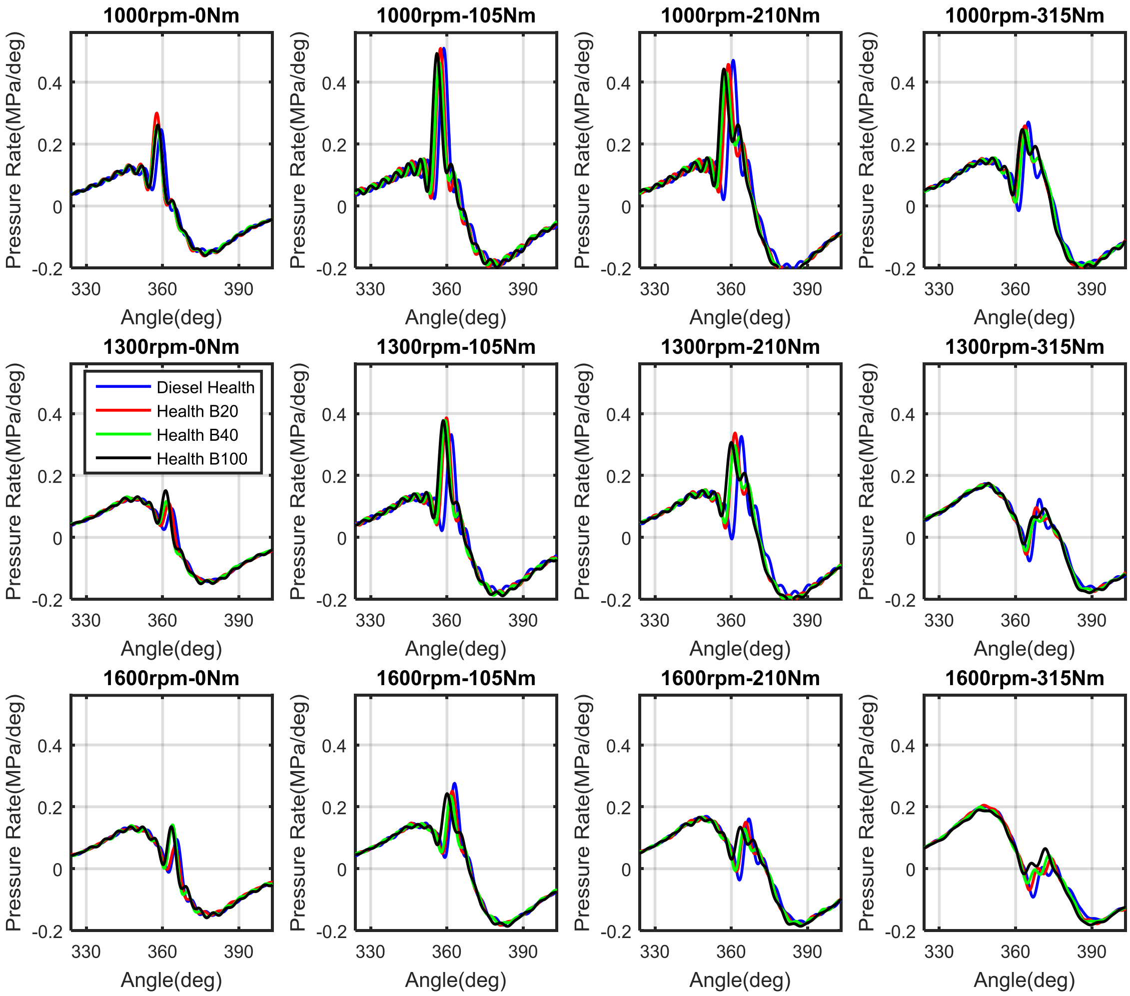


Figure 7-12 In-cylinder pressure rise rate with crank angel for engine running with biodiesel blends B0, B20, B40 and B100 at three engine speeds and four engine loads

The heat release rate is an important parameter characterising the combustion process in CI engines. The plot of heat release rate against cam angle is used to determine the start of ignition, ignition delay time and the peak pressure of heat release. Figure 7-13 shows the heat release rate of a diesel engine running on biodiesel blends B0, B20, B40 B100 at engine speed 1000, 1300 and 1600 rpm and engine loads of 0, 105, 210 and 315 Nm. The engine running with petro-diesel and biodiesel blends shows the same stages of combustion at all load conditions and speeds, but there is some variation in peak heat release rate and ignition delay. The reason for this is because the vaporisation of the fuel spry variation with fuel properties during to ignition delay, at the beginning the curve a negative heat release is observed and after combustion is initiated, the heat release values [208, 209].

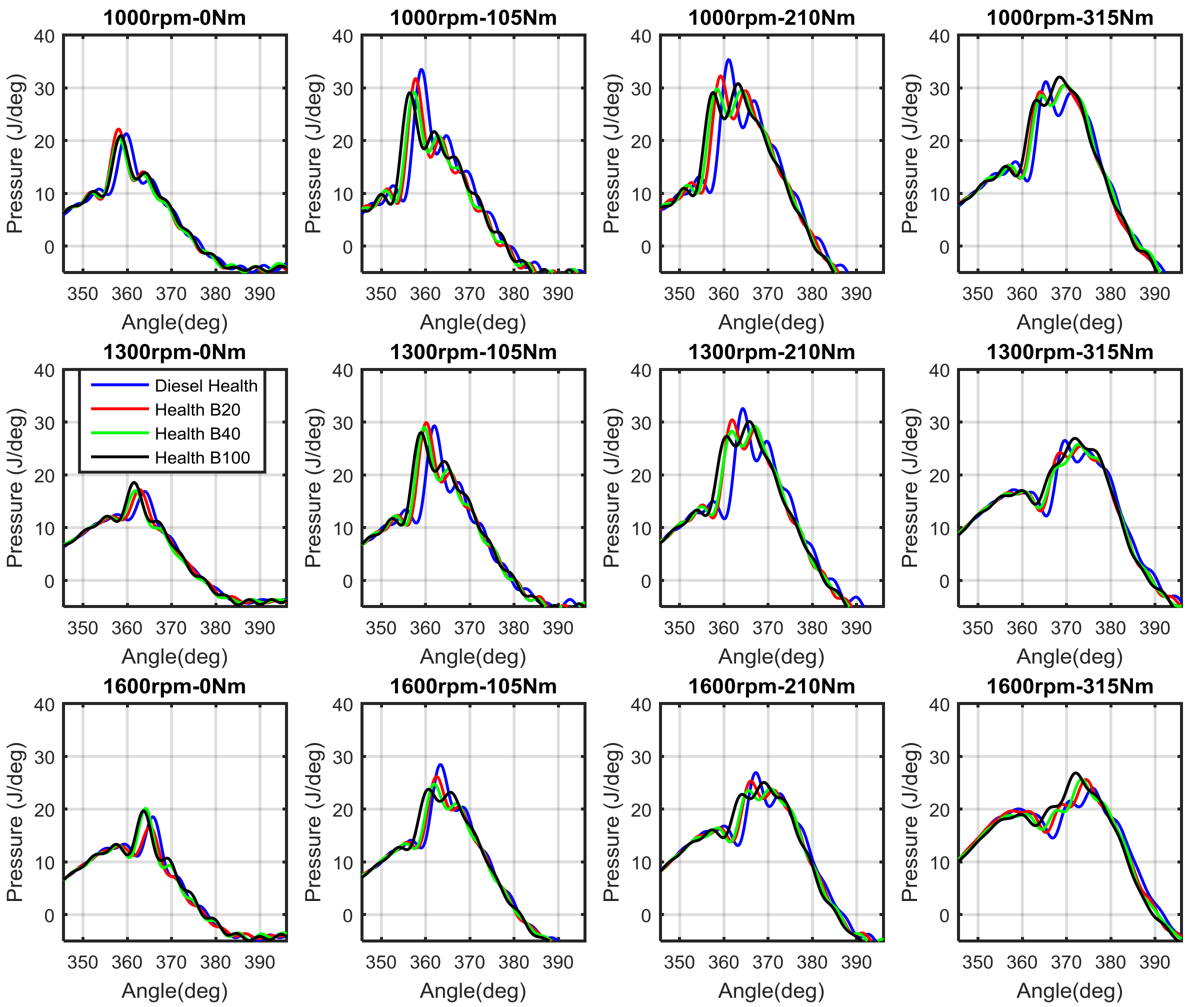


Figure 7-13 Heat release rate with crank angle for CI engine fuelled biodiesel, and biodiesel blends, B20, B40 and B100 at three engine speeds and four engine loads

The variation in heat release rate is attributed to the presence of additional oxygen molecules with the biodiesel fuel which is needed for the air-fuel mix in the cylinder to burn completely also due to the calorific value of biodiesel thus increasing the heat release rate, as see in Figure 7-14.The ignition of the biodiesel blends starts earlier than for petrodiesel. The advance in ignition is attributed to physical factors such as the higher bulk modulus, higher viscosity and greater density of biodiesel [12, 77, 210], [211, 212] and higher cetane number [213, 214]. Some combustion parameters such as peak in-cylinder pressure do not increase linearly with increase in load or speed. Effects of biodiesel blend on the fuel injection system, such as advances in injection are discussed in Section 7.3.

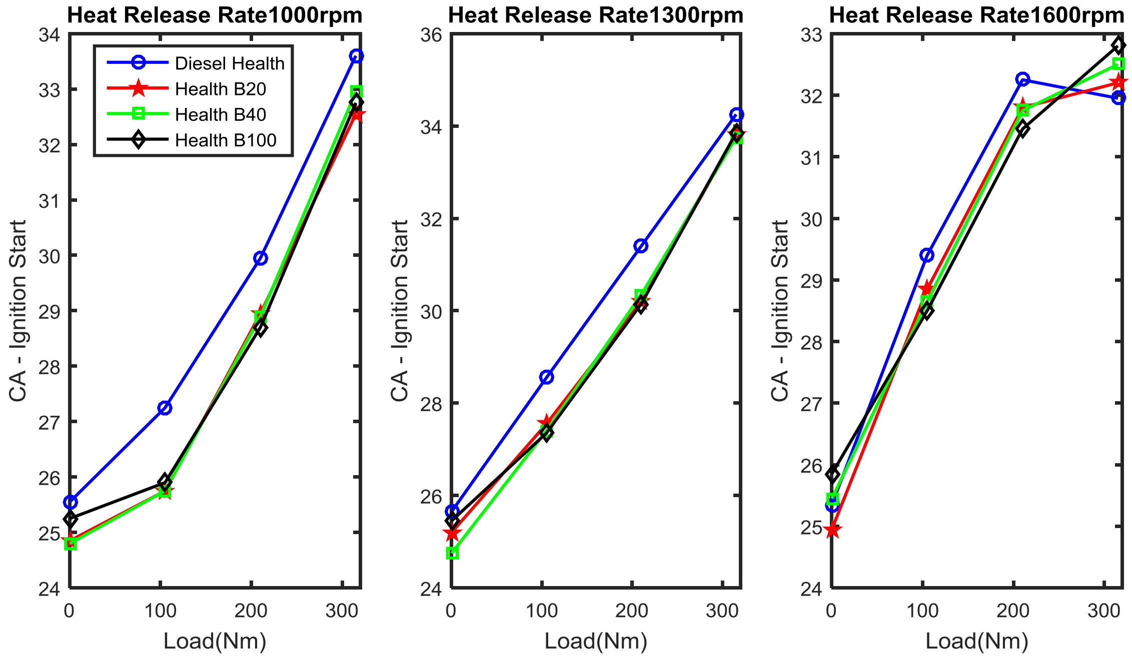


Figure 7-14 Fuel ignition starts with crank angle as a function of engine load for biodiesel blends B0, B20, B40 and B100, for three engine speeds and four engine loads

7.6 Characteristics of Vibration Response of an Engine Running on Biodiesel Fuels

As previously discussed in the literature review, the engine vibration corresponds primarily to the changing in-cylinder pressure that occurs during the combustion process. Figure 7-15 shows the measured in-cylinder pressure and corresponding engine vibration signals as functions of crank angle for an engine load of 105 Nm and three engine speeds 1000 rpm, 1300 rpm and 1600 rpm. The result shows that the major vibration events are well correlated pressure increase and the peaks which confirms that the vibration signals can be will correlated with the in-cylinder combustion stages: the onset of combustion, the maximum pressure and pressuring rises, and the process of residual combustion, which happen around the crank shaft angles of 360° at the TDC of the first cylinder in the tested engine.

Therefore, the detail of such vibration signals is investigated in order to give an accurate indication of the combustion process characterised by the in-cylinder pressures which are measured under different fuels. In addition to use it as the quantitative measures of the influences caused by biodiesels, it also will be based as a reference to compare the diagnostic performance obtained from cylinder head vibrations, pump pressures and vibrations responses.

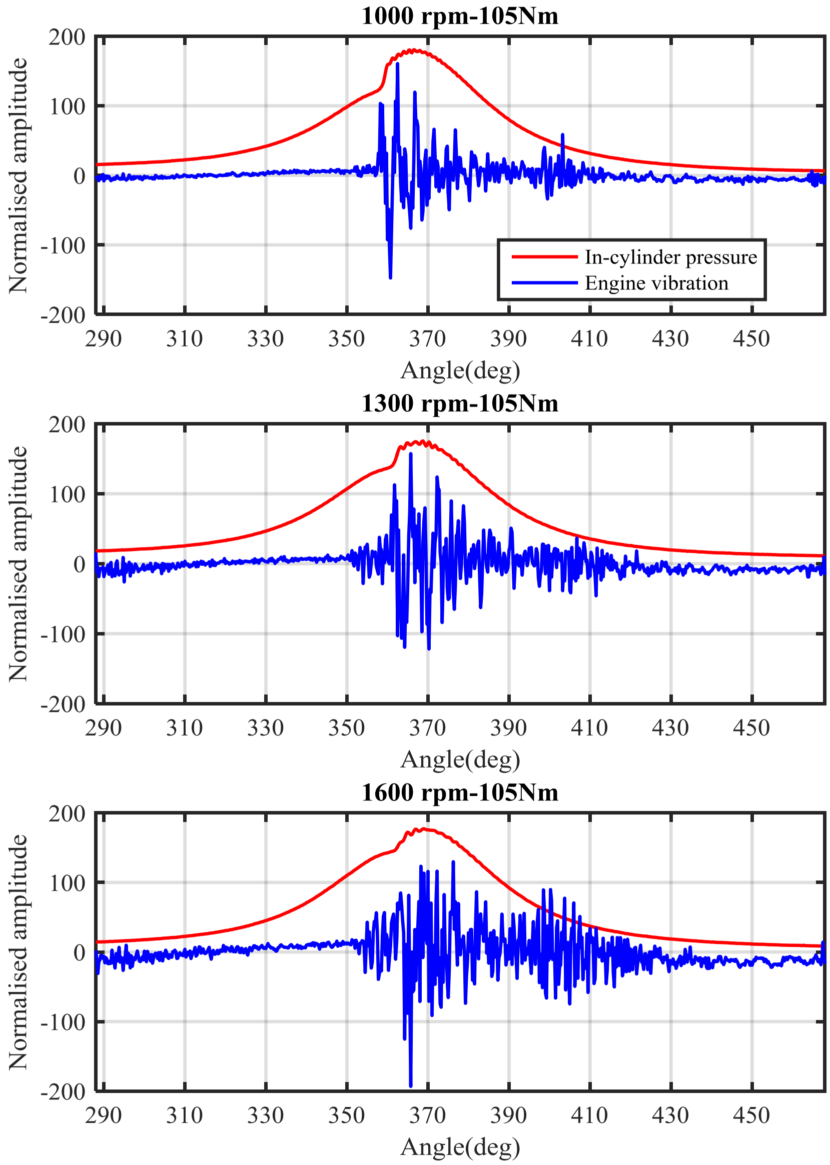


Figure 7-15 In-cylinder pressure and engine cylinder head vibration for one cycle at 1600 rpm and load of 205 Nm, using petro-diesel as the fuel (360° is the TDC of 1st cylinder)

Figure 7-16 presents the cylinder head vibration response as a function of cam angle for one working cycle with the engine running on biodiesel blends B0, B20, B40 and B100, under engine speeds 1000 rpm, 1300 rpm and 1600 rpm with engine a load of 210 Nm. The vibration responses allow a good indication of the combustion event in each cylinder. Moreover, the amplitudes exhibit an increase with engine speeds, showing good agreement with combustion shocks that becomes stronger with engine speeds. In addition, it can be also seen that the vibration events exhibit observable difference between different fuels.

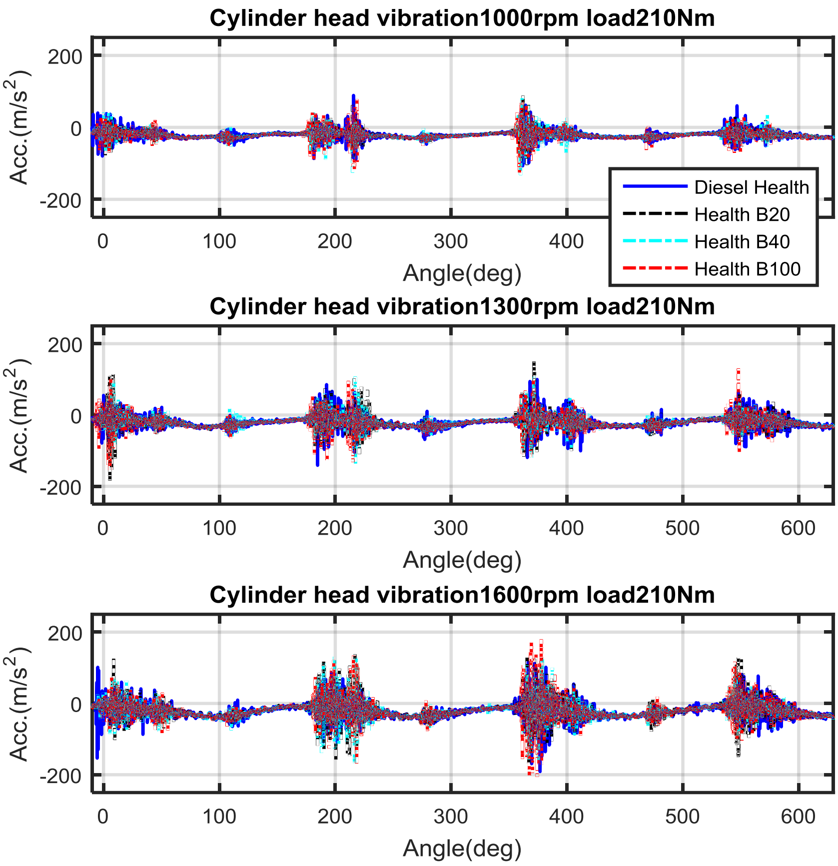


Figure 7-16 Cylinder head vibration signals as a function of crank angle for three speeds and load of 210 Nm for biodiesel blends B0, B20, B40 and B100

To further investigate the vibration analysis for different fuels the RMS value of the vibration signal was calculated and presented in Figure 7-17. It shows that the RMS of the cylinder head vibration signal for biodiesel blends B0, B20, B40 and B100 at four engine loads and three engine speeds. The results clearly show that the vibration levels increase with both speed and loads.

Moreover, biodiesel blends B20, B40 produce the lowest engine vibration levels and that biodiesel B100 and petro-diesel consistently produces the highest vibration levels. B20 produced, overall, the lowest engine vibration level. These vibration features give a better discrimination between different fuels, compared with that of directly found from the in-cylinder pressure in Section 7.3 and therefore, can be good diagnostic indicators for both combustion quality measures and fuel type detection. In detail, vibration signals are investigated in order to give an accurate indication of the combustion process characterised by the in-cylinder pressures under different fuels

In addition to use it as the quantitative measures of the influences caused by biodiesels, it also will be based as a reference to compare the diagnostic performance obtained from cylinder head vibrations, pump pressures and vibrations responses.

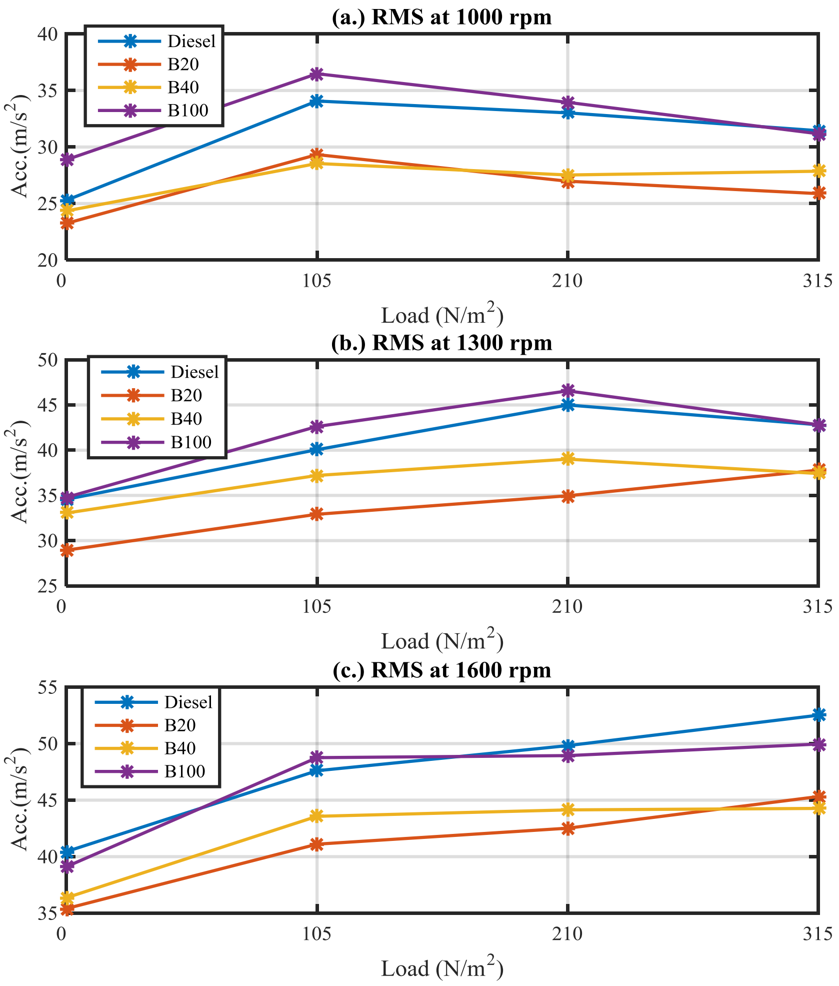


Figure 7-17 RMS of cylinder head engine vibration as a function of load with engine running on biodiesel blends B0, B20, B40 and B100 for three engine speeds

7.7 Summary

This chapter has presented the results of an investigation into FIP and cylinder head vibrations with the engine fuelled by biodiesel blends B0, B20, B40 and B100 by comparing the intrusive pressures and nonintrusive vibrations. The measured fuel pressures at either pump or injector end clearly show about 5% higher amplitude for B100, indicating higher dynamic loads to the FIP equipment. Correspondingly, the vibration at the pump also gives the similar indication, about 20% higher vibration being observed for B100 at the high load and high speed operations.

Moreover, vibration spectrum at the pump can also be a good indication to show the asymmetric fuel supplies between cylinders which may be caused by inventible wear of FIP components wear and lead to engine misfire combustions. The measured vibration signals of a cylinder head under different operating conditions in both the time and frequency domains show high correlations with engine combustion process. In particular, the vibration RMS can be a better indicator for both engine operating conditions and fuel types.

CHAPTER EIGHT

8 DETECTING AND DIAGNOSING THE ABNORMAL CLEARANCE OF VALVE TRAIN BASED ON VIBRATION RESPONSES

This chapter explores the use vibration measurements from fuel pump for evaluating the abnormal conditions of valve clearances when the engine is running on petro-diesel and biodiesel blends at different speeds and different loads. Two such faults are seeded into the inlet and exhaust valve trains respectively. For benchmarking, vibration signal from cylinder head, pressure from pump and in-cylinder are also studied to detect these faults.

8.1 Introduction

The engine consists of cylinder head, cylinder, piston, valve train, and crankshaft. The valves train are important parts of diesel engine. The valve train provides a passageway that allows air-fuel mixture into the cylinder and allows exhaust gas to pass out. Previous studies reported that many faults of engine may be on the valve train [215]. [216]. Faults in engine like valve trains can happen commonly and significantly affected the performances of combustion process therefore power outputs. A several of researchers have studied the valve train condition based on analysis cylinder head vibration, In-cylinder pressure measurements [215] [157] in details in chapter 4.

In this research work, the measurements show good performance in diagnosing such faults of abnormal clearance valve less than 20 %. Obviously they need multiple sensors in monitoring multiple cylinder engines, which involves not only high cost but difficulties in implementation, due to sensor installation and signal cable arrangement onto a compacted engine structure. In addition, the diagnostics may be highly influenced by inaccuracies in separating the vibration response due to combustion from that of valve impacts because they are very close each other.

As shown in Chapter 7, the single channel of vibration of pump can reflects fuel injection characteristics for each cylinder. Once a fault happens in engine valve trains, the combustion generally deteriorates and more fuel supply is required to compromise the deterioration for maintaining the engine output performances. Based on this analysis, this chapter investigates vibration responses of the fuel injection pump in order to find changes in the pump signals that correspond to the additional fuel delivery caused by any valve faults, in order to achieve fault diagnosis. However, as depicted in Chapter 6, this chapter investigates the use of pump vibration to diagnose the intake and exhaust valves that are used to control the flow and exchange of gases into the combustion chambers. Such faults are conventionally investigated based cylinder head vibrations, which give good results but need multiple sensors.

The pump vibration signals are form the experiments in which faults are seeded into the inlet and exhaust valves so that changes are induced to the valve clearances, and measurements made at these abnormal valve train conditions to determine whether the fuel injection is affected under different operating conditions and fuel types. Under normal operating conditions the valve clearance for both inlet valves is 0.3 mm, and the outlet valve of 0.64 mm. The seeded faults increase the clearance of Cylinder 1 into 0.42 mm first for the inlet valve only, and then 0.76 mm for the outlet valve only as describe in section 6.6.3 and Table 6-6. These changes are regarded as small valve train faults as they cause limited influences on the combustion performance, which will be shown by the in-cylinder pressure measurements later on. In addition, vibration signals of cylinder head and pressures of both the pump and the in-cylinder are also examined under different operating conditions and fuel types for benchmarking the diagnostic performances obtained by the pump vibration signals.

8.2 Injection Pressure Measurement based Monitoring

To investigate the changes of the valve faults of interests, fuel injection pressures are compared between different fault cases. Figure 8-1 shows fuel injection pump pressure waveforms of diesel fuel into the first cylinder as a function of crank angle for three engine speeds, 1000rpm, 1300rpm and 1600 rpm, and four loads 0, 105Nm, 210Nm and 315Nm for the healthy and two faulty conditions.

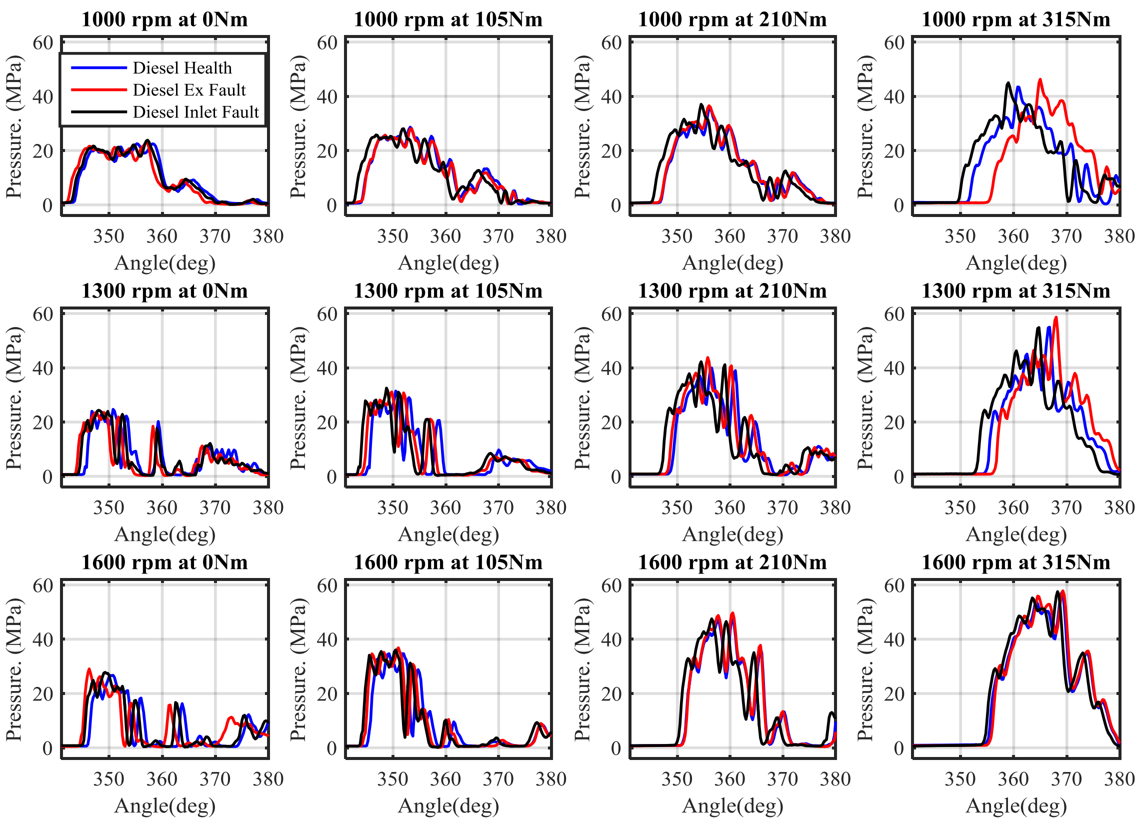


Figure 8-1 Fuel injection pump pressure waveforms as a function of crank angle for three engine speeds and four loads for healthy and two faulty conditions

To better discern any differences, the signal is presented for only crank angles between 340^0 and 380^0. It can be seen in Figure 8-1 that both the pressure amplitudes and overall injection profile are difference between the fault cases and the baseline. So it is clear that the valve train condition has a significant effect on the fuel injection pressure with noticeably different behaviour for each set of valve conditions. For a more comprehensive analysis of pressure measurement, peak pressure, injection time and injection duration have been extracted and compared for the engine with and without the valve faults. Figure 8-2 shows the peak pressure of the fuel injection pump measurement as a function of load, for three engine speeds for petro-diesel and biodiesel blends, B20, B40 and B100 with and without the seeded valve faults.

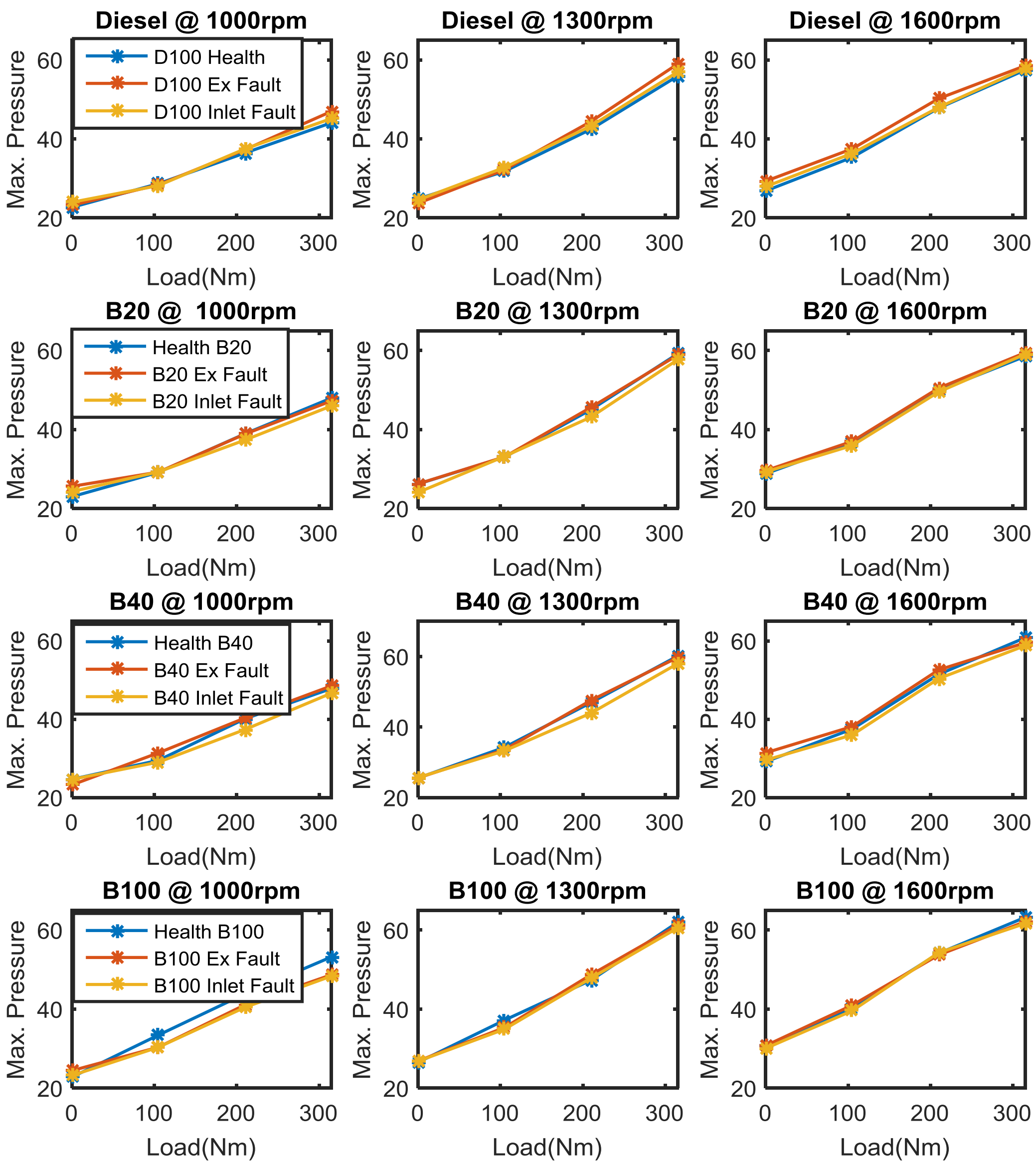


Figure 8-2 Peak pressure of fuel injection pump under different fuel different engine load and two faults valves train condition

The fuel injection maximum pressure with the seeded exhaust and inlet valve faulty clearances varies very little from the healthy condition for all fuels tested. The small differences that occur are due to in-cylinder pressure leaking into the valve train due to the seeded valve faults. Both the time at which the fuel injection into the combustion chamber commences and the duration of the injection time are important parameters in the combustion stage of a diesel engine cycle. Figure 8-3 shows the start of the fuel injection, in terms of crank angle as a function of load for healthy and faulty valves for four biodiesel blends (petro-diesel, B20, B40 and B100). The injection is advanced, compared to the healthy condition, with increase in clearance of either the inlet or exhaust valves. It is also seen these faults most affected the engine, the advance injection effected by the pressure change in combustion chamber with valves clearance fault, even, i.e. most advanced injection, when it was running on blends B100 and B40. That is considered to be due to the properties of the biodiesel fuel.

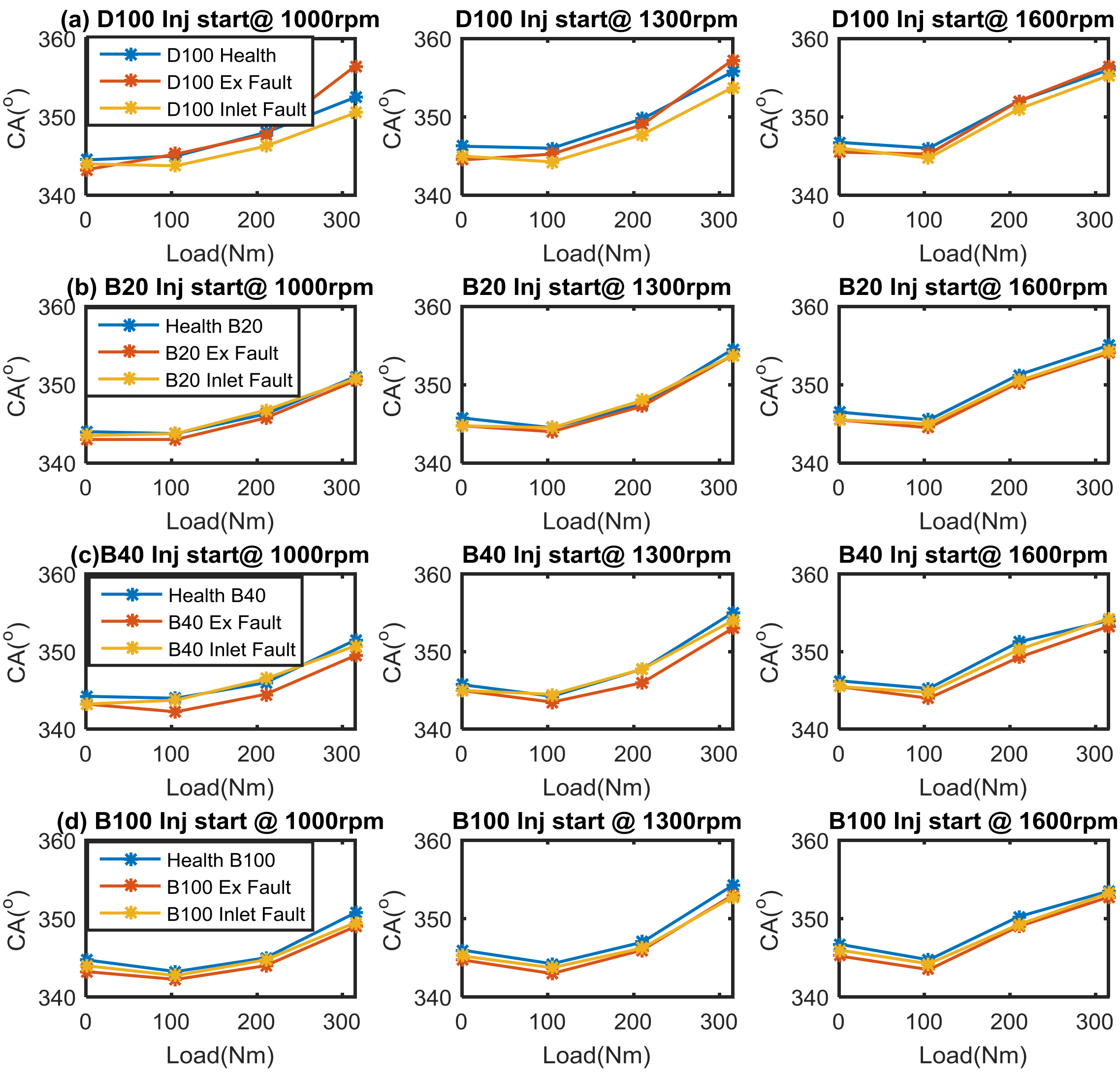


Figure 8-3 Fuel injection start under different engine parameters with valve train fault conditions

Figure 8-4 shows the fuel injection duration for the diesel engine as a function of load, when running at three speeds, and biodiesel blends, B0, B20, B40 and B100, with and without the seeded valve faults. The result shows the injection duration with the faulty valves is, generally, longer than for the healthy condition. The condition of the valve train affects in-cylinder pressure; the faulty conditions caused increased pressure and fluctuations of in-cylinder pressure which affected the fuel injection process.

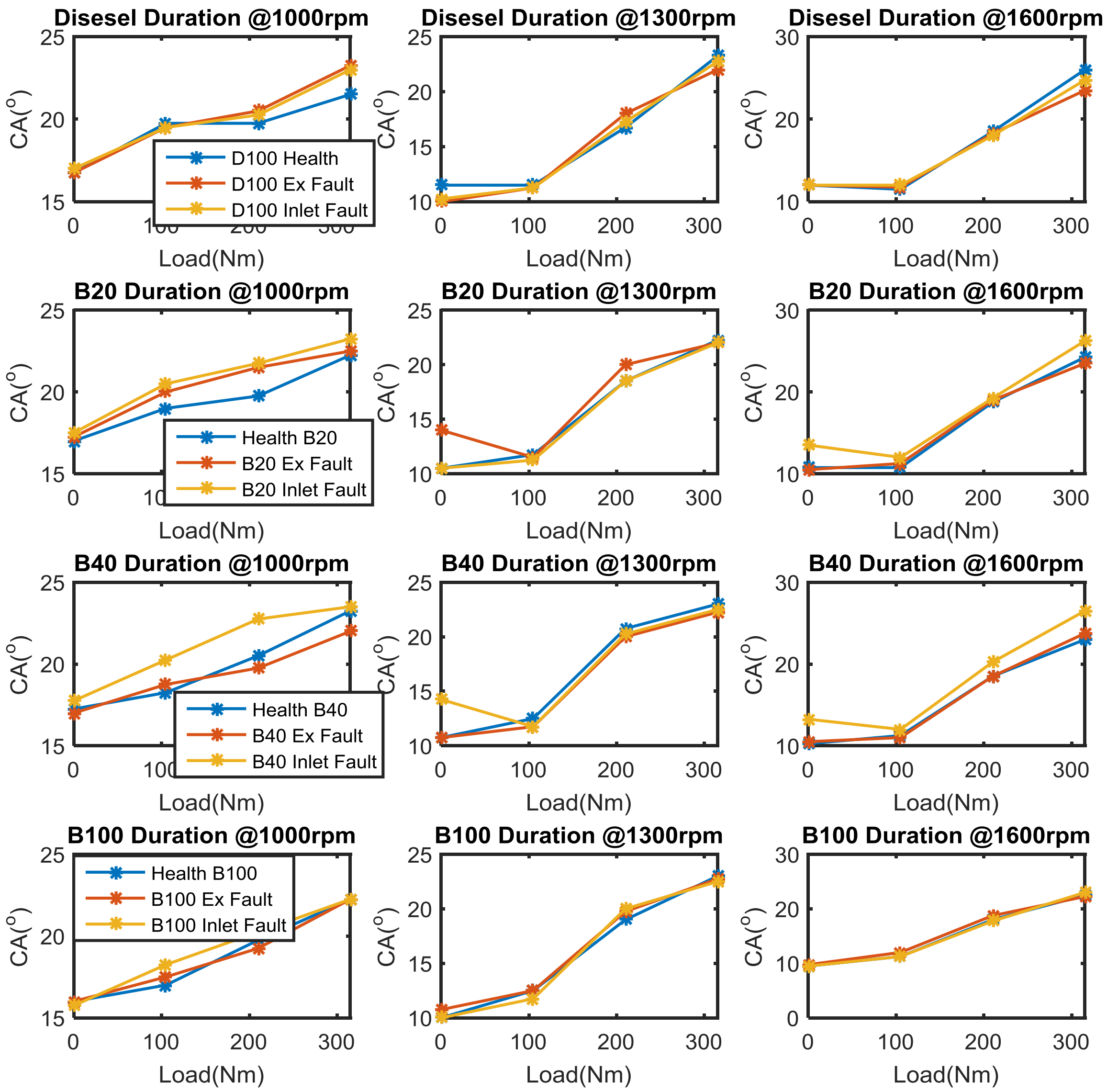


Figure 8-4 Fuel injection duration under different engine parameters with valve train fault condition

Nevertheless from the analysis of the fuel injection pressure and pressure parameters such as peak pressure, injection time and injection duration it is possible to detect the faults in the valve train. The main reason for the increase in FIP pressure and fluctuations in injection start time and injection duration is the difference in pressure between fuel injection and in-cylinder. With the given faulty valve train conditions the in-cylinder pressure increased (see Section 8-3) and that affected the quantity of fuel injected. When using biodiesel blends (B20, B40 and B100) with the faulty valve train, the fuel injection pressure increased with consequent fluctuations in the pressure parameters.

8.3 In-cylinder Pressure based Monitoring

The effect of increasing the inlet and exhaust valve clearances on cylinder pressure can be major factors degrading combustion events occurring inside the cylinder and valve train flow pressures. In particular, the increased clearance will lead to less fresh air taken into cylinder and exhausted gases taken out of the cylinder. Consequently, the combustion performance become lower and so does the power output.

Figure 8-5 shows measured in-cylinder pressures as a function of crank angle, with the engine running at 1000 rpm, 1300 rpm and 1600 rpm, subject to a lower load of 105 Nm for the cases of different valve conditions and fuels tested. The results show clear differences between the engine running with and without the seeded faults. Especially, the combustion events show significant advanced for most of the fuels along with that the pressure amplitudes also exhibit observable changes. This can be a good indication that the residual pressure inside the cylinder is higher as the increased valve clearances lead to smaller valve flow areas and hence the throttle more to the flows. However, the changes show little consistency with the speed, fuel types and fault cases variations.

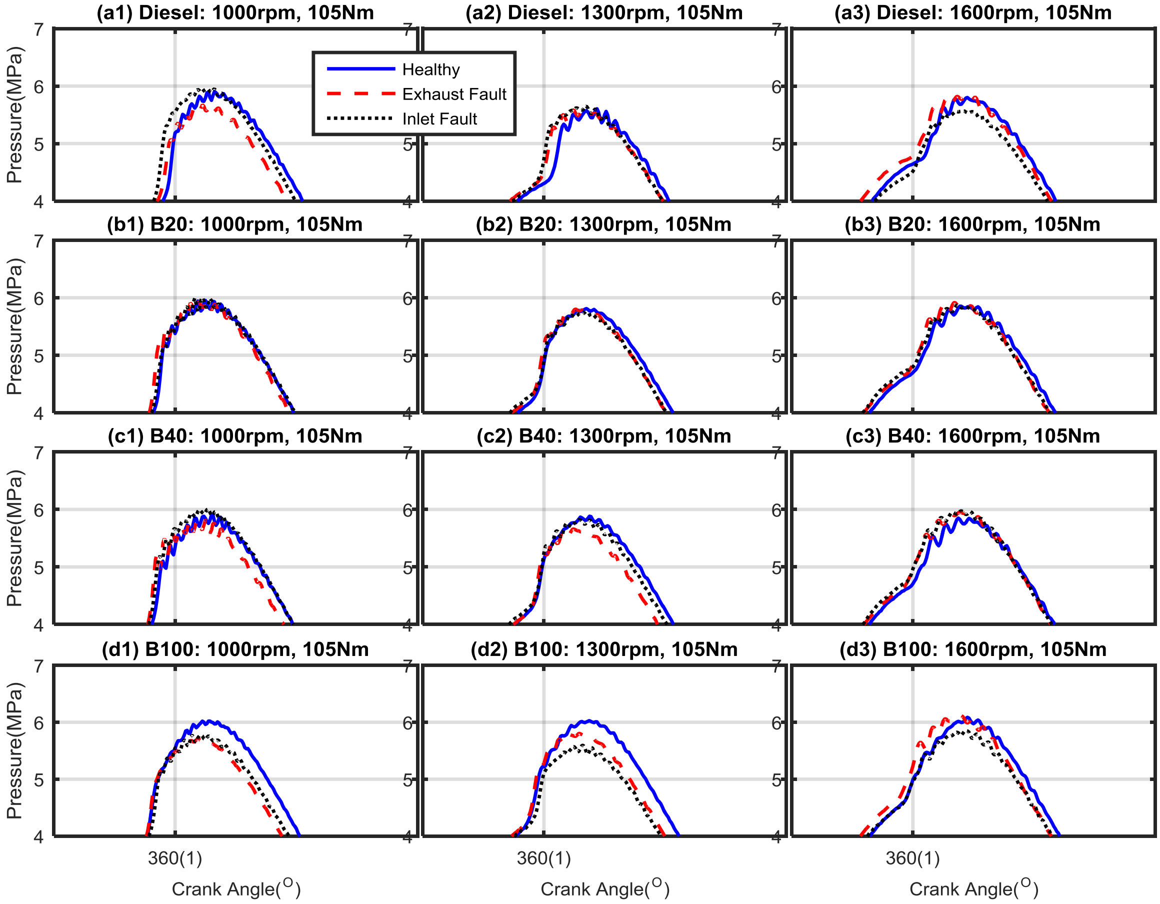


Figure 8-5 In-cylinder pressure waveform as a function of crank angle, with the engine running with different fuelled and speed under load 105Nm

Under higher load operation, the measured in-cylinder pressures are presented in Figure 8-6 and show the function of crank angle, with the engine running at 1000 rpm, 1300 rpm and 1600 rpm for the cases of healthy and two faulty valve conditions and fuels tested. The changes in pressure profiles show similar characteristics as that observed for the lower load. The combustion events show a significant advance for most of the fuels and pressure amplitudes also exhibit observable changes. However, again it is difficult to find changes that show consistency with speeds, oil types, and fault cases variations.

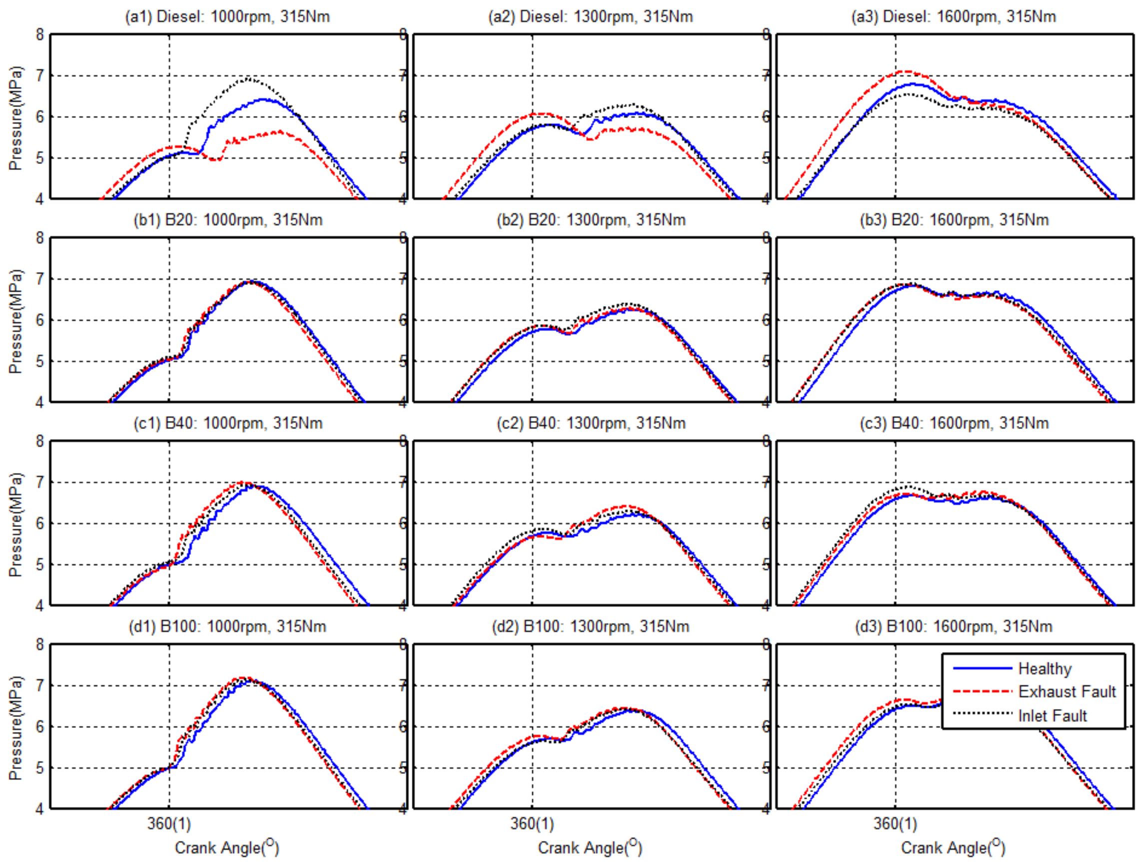


Figure 8- 6 In-cylinder pressure waveform as a function of crank angle, with the engine running with different fuels and speeds under load of 315Nm

To show overall changes of pressure, the indicated mean pressures (IMP) were calculated from the waveforms for all tested cases, which are commonly used as a measure to reflect the changes in both the pressure phase shifts and magnitude changes. Figure 8-7 presents IMP values across different cases. It can be seen that the power output is slightly lower for the two cases of increased valve cleanses, showing lower performance in combusting the fuels. In general, the in-cylinder pressure analysis can be based to detect the problems with incorrect valve clearances. Also the changes in IMP values show that these two faults only produce very small influences on the power outputs.

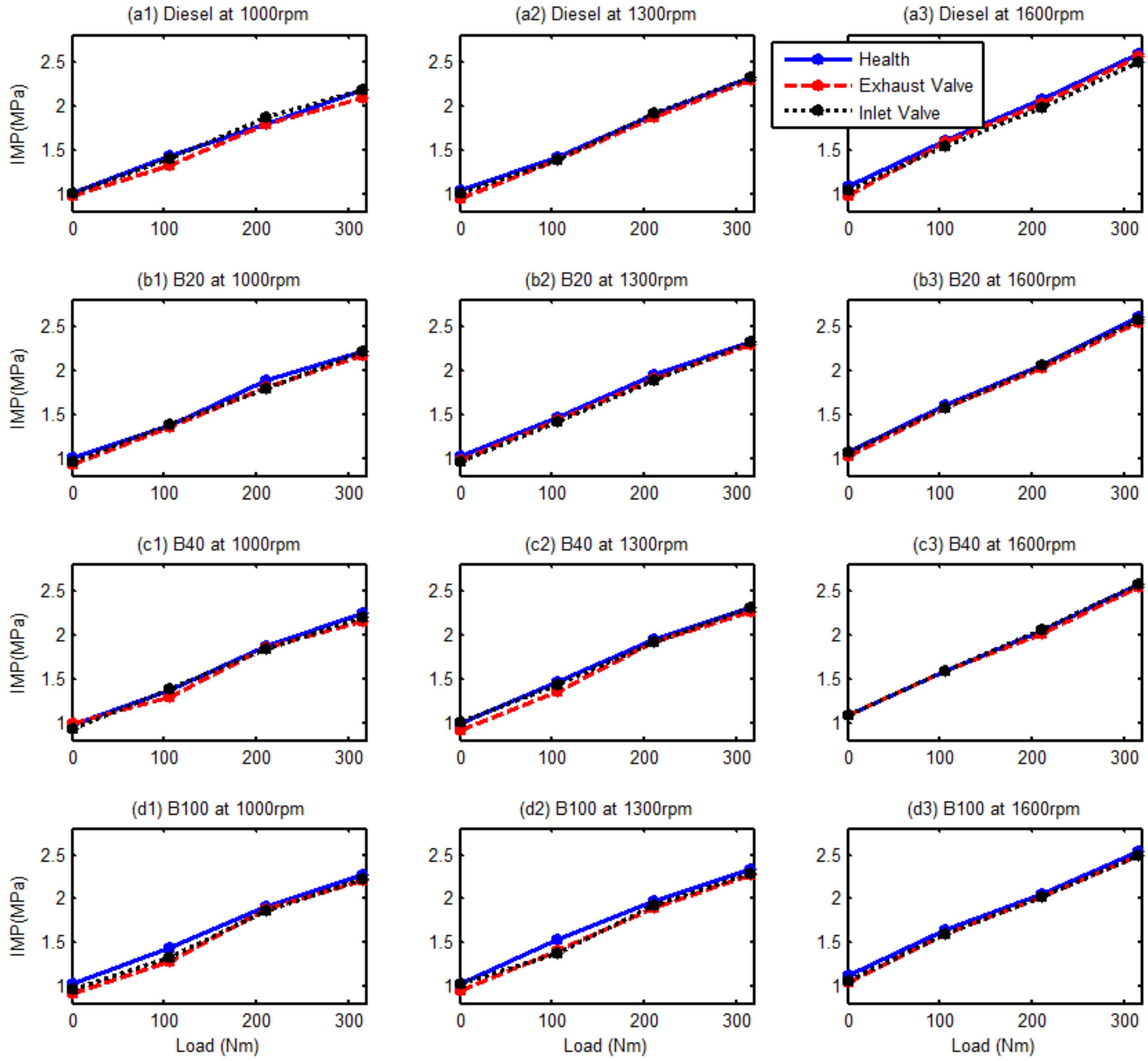


Figure 8-7 Indicated mean pressure (IMP) of in-cylinder pressures with Diesel, B20, B40 and B100 fuels under different operating conditions and fault cases

8.4 Cylinder Head Vibration based Monitoring

Engine valves are designed to control the gas flow into the combustion chamber, the closing and opening times are key characteristics in this process. Four stroke diesel engines require a significant amount of valve movement for the requisite gas input or output related to engine requirements. This can be control by engine cycle. To diagnose the engine train valve fault condition based on engine vibration response with engine running with biodiesel and biodiesel blends.

Figure 8-8 shows the measured engine cylinder head vibrations with the engine fuelled by petro-diesel, at 1600 rpm and load 210 Nm, for healthy condition and with faulty inlet and exhaust valve clearances. The signals show the vibration amplitudes decrease for the increased valve clearances, which is also clear in the middle of the strokes and that after TDC where valve impacts happen for a four cylinder engine. In addition to the smaller valve movement stroke which induces less mechanical impact, the abnormal clearance valve trains also affect the outflow of the combustion gases which cause the valve head to overheat and burn through in the area of the seat's which is the gas is control when the valve is closing that's working like damping between the valve and seat. That is clearly shown on the vibration of cylinder head when decreasing with abnormal valve faults condition. However, these phenomena contribute to an insufficient gas seal between the cylinder head seat and valve. These faults have negative effects on combustion conditions and engine performance.

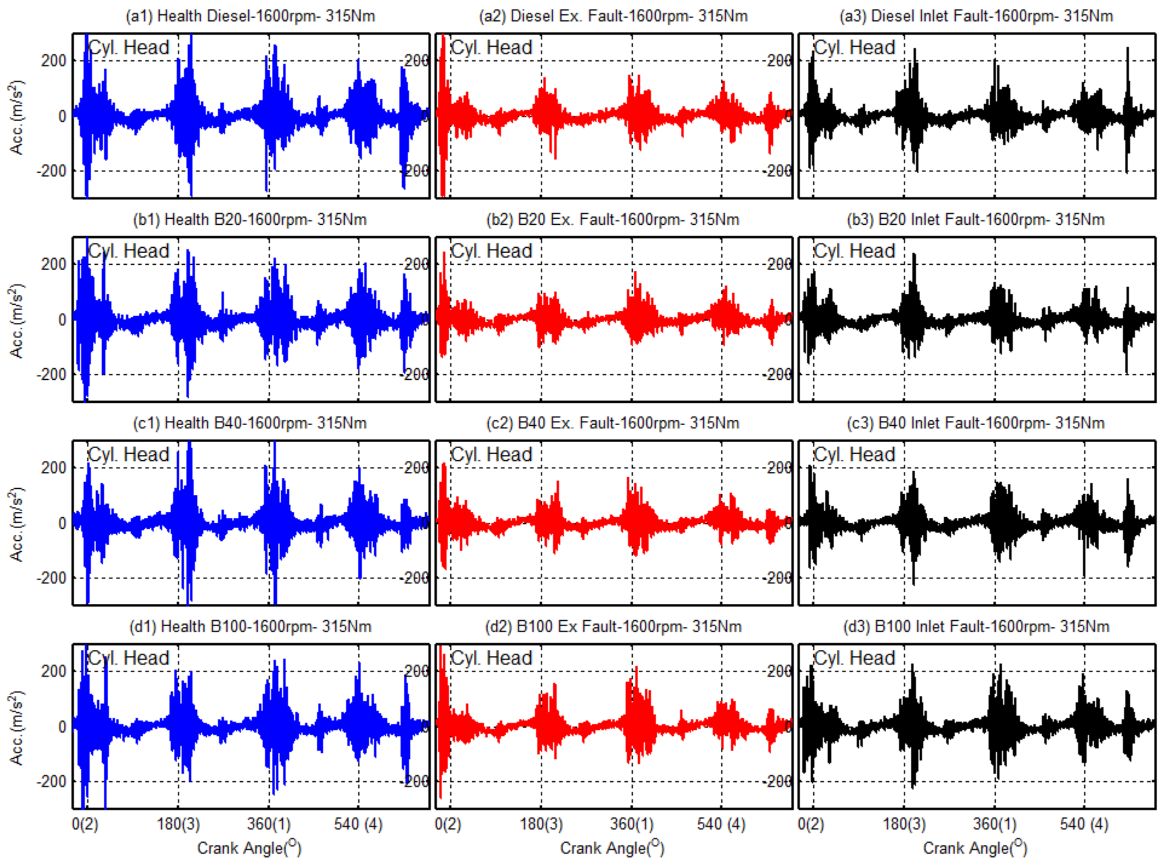


Figure 8-8 Vibration of cylinder head under two cases of faults valve train at engine speed 1600 rpm and engine load 210 Nm

Moreover, the signals exhibit the features of typical impulsive transients due to the effect of the valve impacts and the associated structural resonances of the cylinder head. Therefore, they are depicted by calculating the envelop magnitudes in the frequency from 10 kHz to 30 kHz for the vibration of the cylinder head. This high frequency envelop amplitude, abbreviated as (HFEA), can highlight much effectively on the impulsive transients in the high frequency range by minimising the effect of rigid body vibrations in the low frequency range.

The HFEA as a function of load and comparing results obtained with the engine fuelled by petro-diesel and biodiesel blends B20, B40 and B100 are shown in Figure 8-9. The results showed that the measured vibration levels with the seeded inlet and exhaust valve faults are lower than that of the healthy condition, for all fuels tested. The decrease in vibration with respect to the healthy clearance is due to the effect on combustion gas flow, which, as stated above can reduce valve stroke and cause the valve head to overheat and burn through in the seat area.

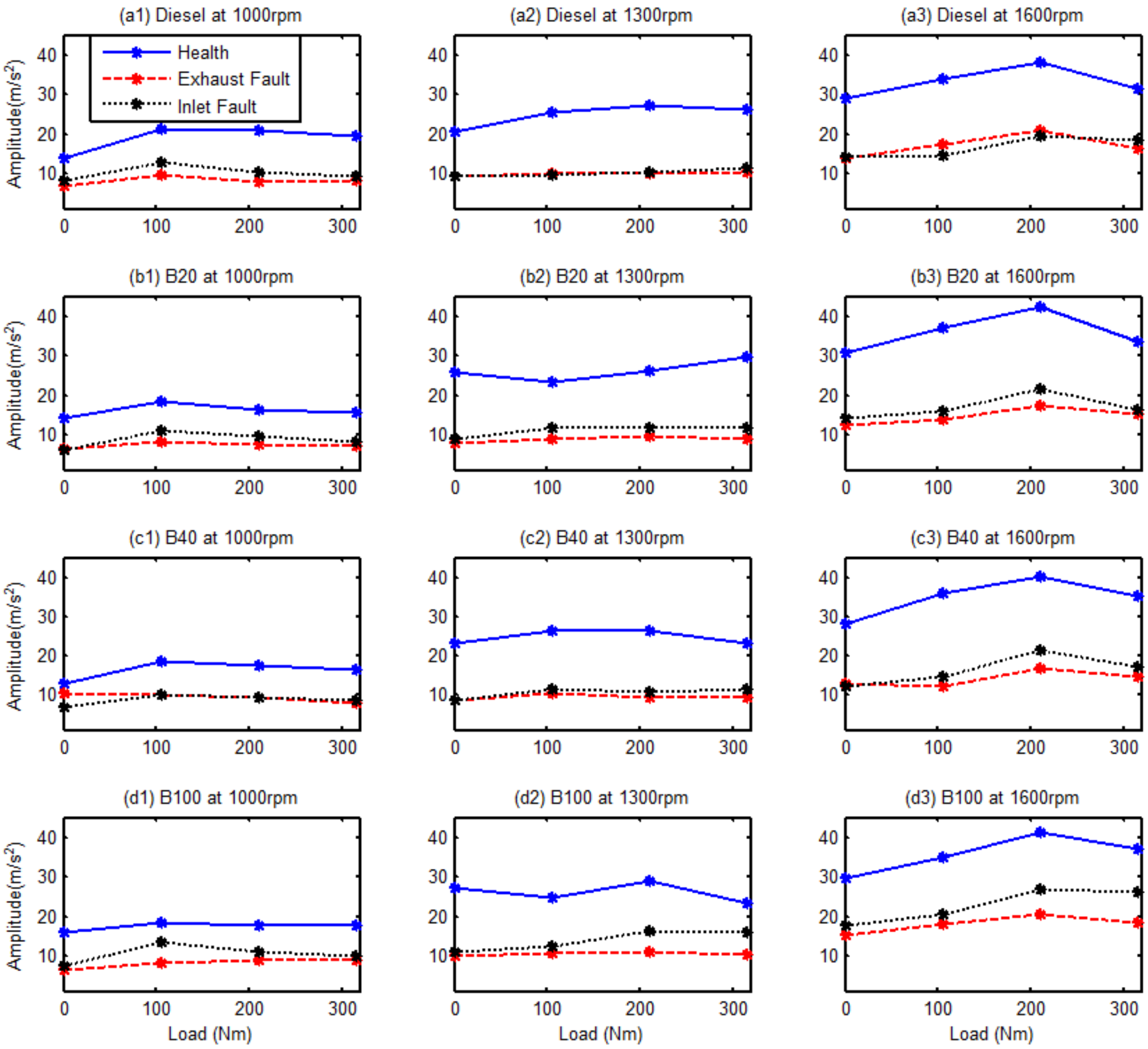


Figure 8-9 High frequency envelop amplitude of the cylinder head for different fault cases when engine running petro-diesel and three biodiesel blends under different operating conditions

In general, vibration from cylinder head can give god indication of increased valve clearances by the reduced HFEA values. However, the degree of severity is probably not accurate as the combustion events which are difficult to be separated out are inevitably included in the values.

8.5 Pump Vibration based Monitoring

Increase of the system pressure with engines heavy duty leads to high effort on high pressure pump design. High pressure of fuel injection pump single plunger is designed for intermediate pressure level and higher capacity related on the amplifier piston ratio. Engine fuel injection pump is fuel lubricated. However, mechanical principle of fuel injection pump is work related to the engine fire order. In this research, the one main objective is to study the effects of engine valve train condition on fuel injection system.

Figure 8-10 shows the fuel injection pressure such as pump pressure and injector pressure with fuel injection pump vibration. The pump vibration signal is associated with the fuel injection pressure. The results show that vibration responses closely correlate with the pressure variations. The high rate oscillations appear in the same period of the pressure pulse. In particular, there are two faults of engine valves train in first cylinder, shown in this Figure (b, c). The results demonstrated the amplitude of vibration pump in first cylinder increasing with exhaust and inlet valves fault condition. The inlet valves faults have higher vibration amplitude than exhaust valve fault condition, that's mean the inlet valves faults have more effects on fuel injection pump. This means the responses are corresponding to the two impacts caused by the opening and closing of the delivery injection fuel valve and needle injector valve. The amplitudes of the transient responses increase consistently with the engine valve train faults, which cause more impact to delivery injection fuel valve under high pressure, because valve train affected the in-cylinder pressure, this effect cause more injection pressure to deliver the fuel quantity in this engine cylinder.

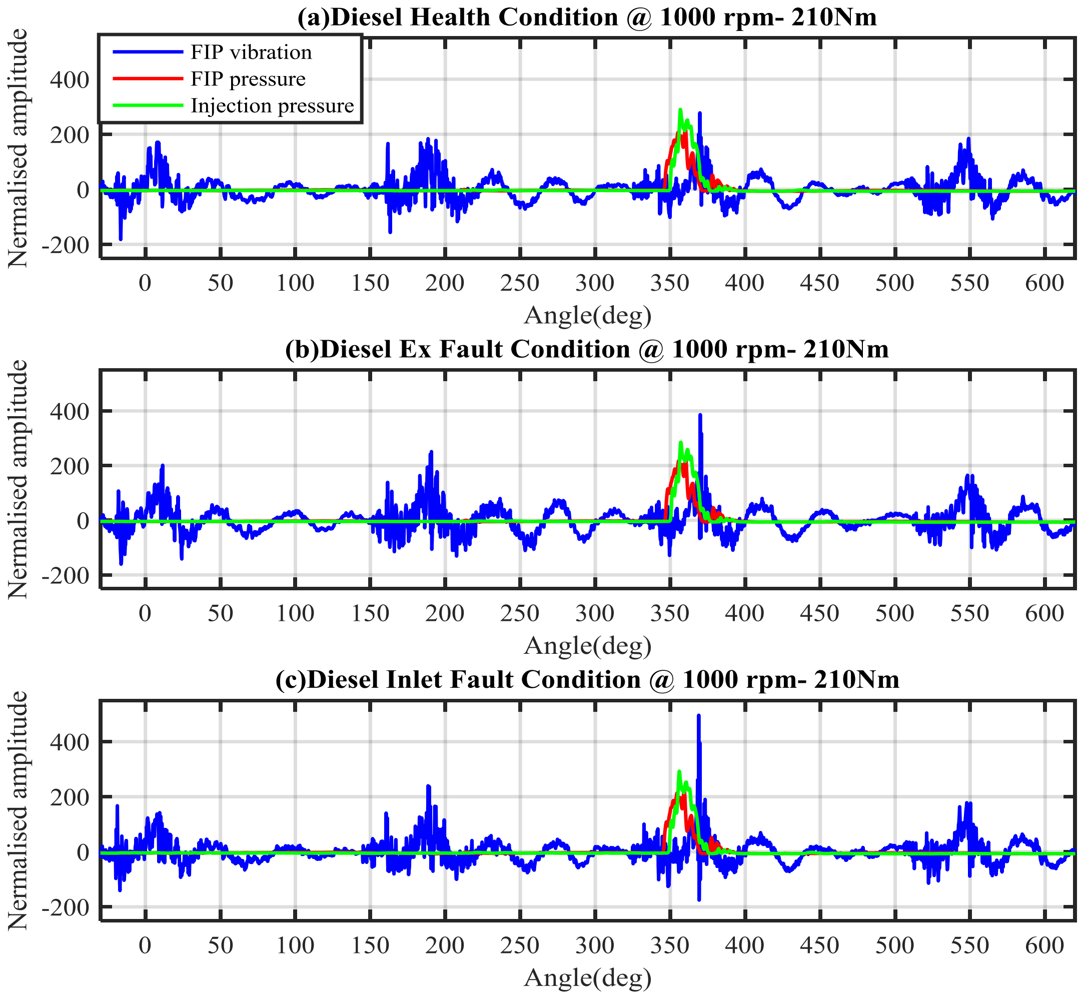


Figure 8-10 FIP vibration waveform with FIP pressure and injector pressure for the baseline and valve faults

FIP vibration responses when the engine is running on biodiesel blends, B0, B20, B40 and B100 as a function of crank angle, at engine speed 1600 rpm and load 210 Nm, for the two seeded valve faults is shown in Figure 8-11. It can be seen that, for all the fuels tested, the vibration responses increase for injection events around 360° where the valve train fault is presented in Cylinder 1. Also increasing the clearance of the inlet valve has a greater effect on fuel injection pump vibration than the exhaust valve. The reason is that the inlet valve train fault directly affects the start and duration of the combustion stage more than exhaust valve train fault condition.

Based on these observations and understandings, it can be found that the relative vibration amplitudes between different injection events can be a good indicator of each injection, which therefore can be based on to diagnose the faulty cylinder, rather than using measured fuel injection pressure.

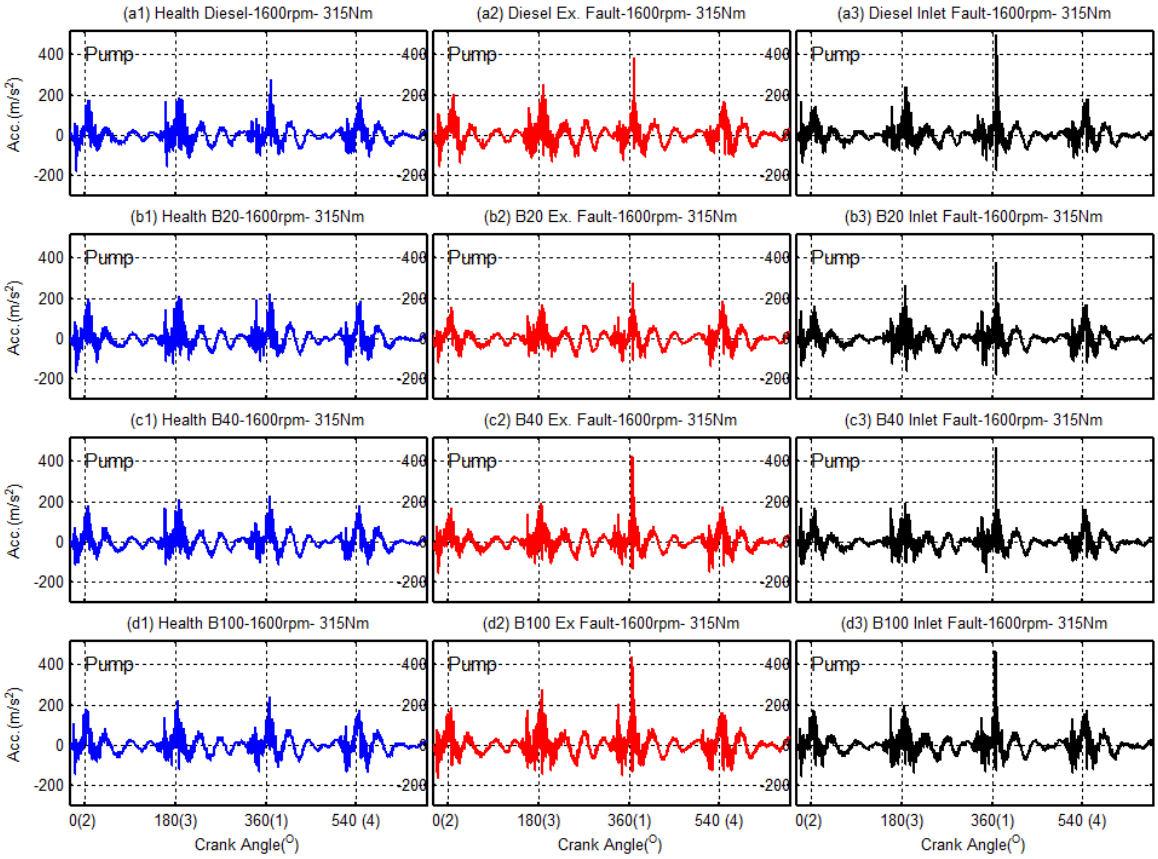


Figure 8-11 Vibration waveforms of fuel injection pump for baseline and valve faults when engine runs wiith diesel and biodiesel blends at speed of 1600 rpm and load of 315 Nm,

In addition to the low frequency osicllations caused by the resonace effect of the cam-pluger system, the vibration exhibits disdinctive high frequency contents due to the magnification of the impacts of delivery valves by pump structrue resenances. In the same way as chracterise the head? vibration. HFEA values were calculated as a general measure for represeting the changes in signals due to fuel dilivery changes.

Figure 8-12 presents the vibration level in HFEA values for the fuel injection pump with the engine running at biodiesel and biodiesel blends under different operating conditions. The results show that both the abonormal clearance valve trains cause an increase in vibration levels which are more distinctive in higg load and speed operations. Comparatively, B100 show less increase across different operating conditions as its high viscosity can have more dampening effect to the mechnical impatcs happening in delivery valves. Based on these changes, it can be concluded that pump vibrations signals can be also used to detect and diagnose the valve train faults even though the happen far away from the pump with anlysis the vibration based on HFEA motheds.

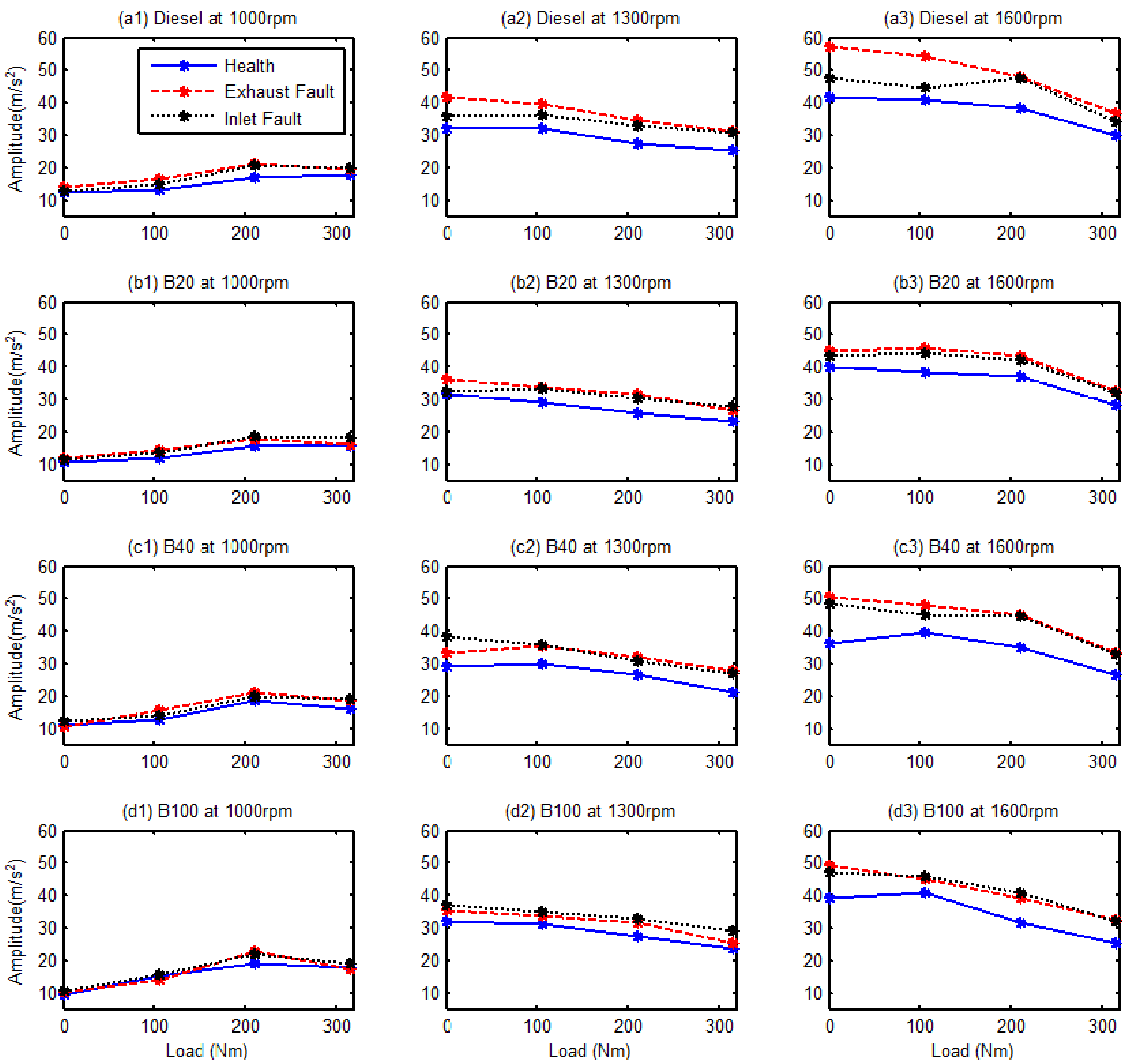


Figure 8-12 High frequency envelop amplitude of FIP vibration for different fault cases when engine running with biodiesel, biodiesel blends and diesel fuel under different operating conditions

8.6 Summary

It has been concluded that the measurement and analysis of pump vibrations can produce a good indicator of the condition of the valve trains. In particular, the vibration levels become higher due to the faults as a consequence of additional fuel supply to compromise the loss of overall power caused by poor combustion performance on the cylinder with valve faults.

In the meantime, the head vibration also can indicate the faults by a reduced level of vibration due to an effect combined reduced valve movement stroke with gas flow dampening. Moreover, B20 and B40 exhibit the similar changes with that of petro-diesel in HFEA values whereas B100 shows less increased values. However, the pressure measurements are not very clear in representing these small changes in valve clearances for both the exhaust and inlet valves.

CHAPTER NINE

9 CONCLUSIONS AND RECOMMENDATION FOR FURTHER WORKS

This chapter summarizes the achievements and conclusions of this research in association with the objectives set up in Chapter One. It has also highlights the major contributions to knowledge. The chapter ends by addressing the future work that would help to further advance subjects topics which have been investigated in this research.

9.1 Review of Research Objective and Achievements

This chapter describes the research contributions and achievements. The most important achievement is that novel results have been obtained using a technique developed for online monitoring of the fuel injection system of a CI engine. Specifically, the monitoring of the fuel injection system with the engine running on petro-diesel and biodiesel blends using vibration measurements made on the fuel injection pump to detect abnormal clearance valve. There are a number of achievements for this research study as described in following list.

Objective one: To gain understandings of the relative physical properties of petro-diesel and biodiesel blends, including such parameters as fuel density, viscosity, bulk modules, heat value and their associated temperature characteristics.

Achievement one: All experimental researches of fuel properties have been carried out at applied Science laboratory (UoH), including measurements of fuel density, viscosity and heat value for the petro-diesel and biodiesel blends. The experimental results showed that the physical properties of petro-diesel and the biodiesel blends, B100, B20, B40 were sufficiently different, especially the higher density and viscosity of biodiesel, to affect the fuel injection parameters and change the high pressures within the fuel injection system, see chapter 2.

Objective two: To analyse influences of different fuels on the dynamics of engine fuel injection using FIP and fuel injector pressure measurements during steady engine operation. Fuel injection parameters such as peak pressure, injection time and injection duration have been studied to understand the different impact of biodiesel blends on the fuel injection dynamics.

Achievement two: A comprehensive CI engine test rig was developed featuring key instrumentation which measured both FIP pressure and fuel injector pressure. It was found, the dynamic pressure fuel injector was delayed and higher amplitude than the FIP pressure due to the different mechanisms and processes of the both FIP and injector. Also, FIP and injector pressure increase with both engine load and engine speed to order to inject more fuel into the combustion chamber, see section 7-1

The CI engine fuel injection has been tested with petro-diesel, biodiesel and biodiesel blends. The fuel injection parameters such peak pressure, fuel injection timing and fuel injection duration have been measured and analysed. The effects of biodiesel blends on fuel injection parameters were comparing with petro-diesel and quantified see section 7-2.

Objective three: To have a full knowledge of different techniques capable of non-intrusive monitoring and diagnosing engine conditions by reviewing the literatures.

Achievement three: Condition monitoring techniques of CI engine fuel injection and combustion process were reviewed see chapter 3. Numbers relevant of vibration condition monitoring techniques are discussed to contribute in the understanding of the fuel injection dynamics and behaviour, and the development of a proper on-line condition monitoring technique for fuel injection system, based on experimental and simulations to studies of the dynamic fuel injection with biodiesel fuel and biodiesel blends, also develop condition monitoring for diagnostic and detection abnormal clearance of engine train valve based on fuel injection pump vibration responses.

Objective four: To gain more insight the influences on the dynamics fuel injection by developing a mathematical model of the high pressure injection equipment and thereby carry out systematic numerical simulation studies of the fuel supply equipment operated under engine running with biodiesel and biodiesel blends.

Achievement four: A mathematical model of the high pressure fuel injection system was developed to analyse the effects of petro-diesel and biodiesel blends on the fuel injection equipment. The main impact was on the fuel delivery valve and fuel injector needle. The simulations of the pressure delivery valve and fuel injector were assessed by experimental measurements of pressure parameters such as injection duration, peak pressure and impact of delivery valve and injector needle valve, see section 5-8.

Objective five: To obtain the vibration characteristics of the fuel injection equipment, and investigate effective methods for analysing the non-stationary vibration signals for CM and diagnostics, which is based on the mechanical impacts within the structure of the engine fuel injection equipment as related to the different fuels.

Achievement five: The vibration response data collected from the accelerometers was analysed. Initial emphasis was on the time-domain signal, but the signals were also transformed to the frequency domain and interrogated. Each of the time domain and frequency domains, frequency domain range processing methods was evaluated for its usefulness in monitoring, detection, diagnosis and evaluation of severity level. As a result the vibration response is used with measurements of fuel injection pressure to understand and improve the vibration signal trend with method analysis. Also the vibration response can be used to detect variation in injection parameters (such as timing and impact) for each fuel injection 7-2 and 7-3.

Objective six: To study and understood the consequence of fuel injection dynamic behaviour changes with biodiesel and its blends on engine combustion process. In-cylinder pressures and engine vibration have been used to measure quantitatively the effects of biodiesel on engine combustion processes.

Achievement six: The effects on fuel injection behaviour and combustion process of different fuels were tested experimentally. In-cylinder pressure and engine vibration were measured and analysed. In-cylinder pressure, pressure rise rate and heat release rate were investigated. As a result, the effects of biodiesel blends on in-cylinder pressure and engine vibration have been quantified see section 7-4 and 7-5.

Objective seven: To further verify and improve the proposed online condition monitoring techniques to diagnose combustion changes due to valve train faults by analysis fuel injection pump vibration.

Achievement seven: Engine fault detection and diagnosis has been performed using fuel injection pump vibration for abnormal valve clearances in the valve train. Each fuel injection vibration can be inducted with each cylinder valve train condition, and comparisons between inlet valve and exhaust valve condition have been analysed, see section 8-2.

Objective eight: To evaluate the performance of vibration based engine detection of abnormal clearances in the valve train, with the engine fuelled with petro-diesel and biodiesel blends. In-cylinder pressures and engine vibration have been used to measure quantitatively the engine combustion process for the different valve train conditions with the different fuels.

Achievement eight: The effects of abnormal valve clearance on the engine combustion process with petro-diesel and biodiesel blends were measured using in-cylinder pressure and engine vibration. As a result, the effects of biodiesel blends on in-cylinder pressure and engine vibration have been quantified see section 8-3and 8-4.

9.2 Conclusion of the Results Work Study

This research work is directed towards the investigation of different engine parameters of a CI engine injection system fuelled with petro-diesel and biodiesel blends. That has been done both experimentally and with a specifically developed mathematical model. Moreover, a novel fuel injection pump vibration technique has been developed to diagnose the condition of the engine combustion process. The following conclusions have been drawn from this research study.

Conclusion one: The fuel density, kinematic viscosity and heat value of the biodiesel and biodiesel blends (B20 and B40) and B100 from waste cooking oil feedstock have been measured. As the biodiesel fuel content increases, the fuel density and the viscosity of the biodiesel blend increases. Nevertheless, the low heat value decreases with increasing the biodiesel content. Based on the results in chapter 2, it can be concluded that, the biodiesel blends have different physical properties comparing to petro-diesel.

Conclusion two: Developing the fuel injection system dynamic model, it was found that the pressure in the fuel injector is higher and delayed with respect to the pressure of plunger, fuel delivery valve and pipeline fuel. That is due to the compressibility of fuel, spring forces, reflected pressure waves, etc.

Furthermore, the properties of the biodiesel blends such as fuel density and bulk modules affect the dynamics of the fuel injection system, especially of the delivery valve and fuel injector needle. It has been found that, when the density and bulk modules of the biodiesel increase, each component pressure of the fuel injection system increases as does the injection duration.

The use of biodiesel blends causes changes in the velocity and displacement response of the delivery valve, advancing the fuel injection, generating higher pressure amplitude and a longer injection time compared with petro-diesel. These effects will shorten the life of the fuel injection system.

Conclusion three: Engine operation conditions affect the fuel injection pressure, primarily an increase in either engine load and engine speed leads to a corresponding increase in the fuel injection pressure. In terms of source fuel injection pressure, increase in engine load appears to have a stronger effect than corresponding increases in engine speed. The research has increased the accuracy of measurement for monitoring and diagnosis of changes in fuel behaviour.

Conclusion four: This experimental study has confirmed that the injection pressure waveforms show higher peak values and advanced injection for biodiesel blends (B20 and B40) and B100 due to their higher densities, viscosities and bulk modules. The higher dynamic pressure upon the fuel injection pump and injector may reduce the service life of the fuel injection system.

Conclusion five: After investigating the fuel injection dynamic impact with the engine running on biodiesel blends, the vibration response of the FIP indicated that in both the high and low frequency ranges the vibration levels generated by the impacts of the fuel delivery valve generally increased with the proportion of biodiesel in the blend. For CM purposes the vibration measurement give a good indication of the related dynamic pressure trend behaviour with fuel properties.

Conclusion six: It can be observed that using biodiesel has many effects on the fuel injection system which clearly affect the engine combustion process. It has been found that peak in-cylinder pressure of the engine running with biodiesel blends is slightly higher than the engine running with petro-diesel.

When using biodiesel blends the fuel injection and ignition stage are seen to advance compared to petro-diesel. However, the main reason for a higher in-cylinder pressure with a CI engine fuelled by biodiesel blends is due to advanced combustion being initiated due to the different physical properties of biodiesel, such as viscosity, density and bulk modulus.

Conclusion seven: To observe the consequences of fuel injection using biodiesel on the engine combustion process, the RMS value of time domain signal of the engine vibration was used. The RMS value showed that, the engine vibration depended on the combustion cylinder pressure variation. Thus, that can be determined the engine vibration which has the potential for use as an indicator of engine combustion process instead of using in-cylinder pressure.

However, the RMS value of the time domain of the engine vibration signal under different engine operation showed that biodiesel blends B20, B40 produced the lowest engine vibration levels and that biodiesel B100 and petro-diesel consistently produced the highest vibration levels.

Conclusion eight: Analysis of fuel injection pump vibration signal with a increase in inlet and exhaust valve clearances with the engine fuelled by petro-diesel and biodiesel blends revealed that, the vibration signal clearly showed the indicted with condition of valve train abnormal clearance each engine cylinder based on angular domain (fire order). That was due to the fluctuation in the combustion stage in-cylinder pressure because fuel injection pressure depended on valve train condition.

With the engine fuelled by biodiesel blends, with abnormal valve clearance and under different engine operation it was concluded that, abnormal inlet valve clearance had greater effect on fuel injection and the processes within the combustion chamber than the excessive clearance of the exhaust valve. However, the engine running on biodiesel blends had lower vibration levels with abnormal valve clearance compared with the engine running on petro-diesel. That may be due, as stated above, to the different physical properties of biodiesel, such as viscosity, density and bulk modulus compared to petro-diesel.

Conclusion nine: The analysis of engine body vibration response with abnormal inlet and exhaust valve clearance with the engine running on biodiesel blends showed that the level of vibration was lower than for the engine running on petro-diesel.

Conclusion ten: Analysis of measurements made, including, fuel injection pressure, fuel injection pump vibration, in-cylinder pressure measurements, engine vibration measurements, and analysis of the results, demonstrates that, fuel injection pump vibration response can be used to monitor the fuel injection system and diagnose abnormal valve train clearances for each cylinder of the diesel engine.

9.3 Research Contribution to Knowledge

This thesis seeks to introduce several new aspects and research strategies for linking online techniques for the CM of a diesel engine. The major contributions to knowledge in this research work can be summarised as:

Contribution one: The FIP vibration can be used for monitoring the fuel injection system of a CI engine and the detection of faults. There has been no published research using FIP vibration to monitor fuel injection behaviour. This work addresses that knowledge gap.

Contribution two: There has been no published literature dealing with the correlation of fuel injection pump vibration with fuel injection pressure and fuel injection pressure parameters.

Contribution three: The ability to measure fuel injection pump vibration and effectively classify the fuel properties which significantly affect the fuel injection system provides novel information, and a non-intrusive method to monitor fuel injection systems.

Contribution four: The impact quantification method based on the mathematical model is an original contribution and can be beneficial to providing quantitative information on the effects of fuel properties (biodiesel's) on the fuel injection system and engine combustion performance.

Contribution five: This research work reports for the first time on the development and deployment of a novel engine combustion diagnostic based on fuel injection pump vibration.

Contribution six: This research work provides a new strategy for monitoring CI engine fuel injection and diagnosis of a CI engine valve train with abnormal valve clearances. A non-intrusive measurement obtained from the vibration of the FIP.

9.4 Further Research Suggestions Recommended

The preliminary great deal of research study has been undertaken as part of this study to understand and investigate the techniques of signal processing for non-stationary signals analysis in condition monitoring of CI engine. In order, to be more extensive research work was to be undertaken some key recommendations should be considered.

Recommendation one: CM implementation, powerful and effective signal processing techniques should be developed for feature extraction. The methods must be able and informal to implement using the measured signals.

Recommendation two: Further experimental research work is needed to investigate and address which have greater effect on the life of a fuel injection system; fuel properties or abnormal clearance in the valve train.

Recommendation three: Further investigations and extension of the mathematical model for an abnormal clearance valve train to include fuel injection dynamic pressure and in-cylinder pressure with the engine combustion parameters.

Recommendation four: The signal processing techniques used in this research were limited to only time and frequency domain analysis. Further investigation, using more advanced techniques, is required to help improve this method's capability for engine fault detection.

10 APPENDIX

Engine power carve, the engine operation test did based on the engine power carve.

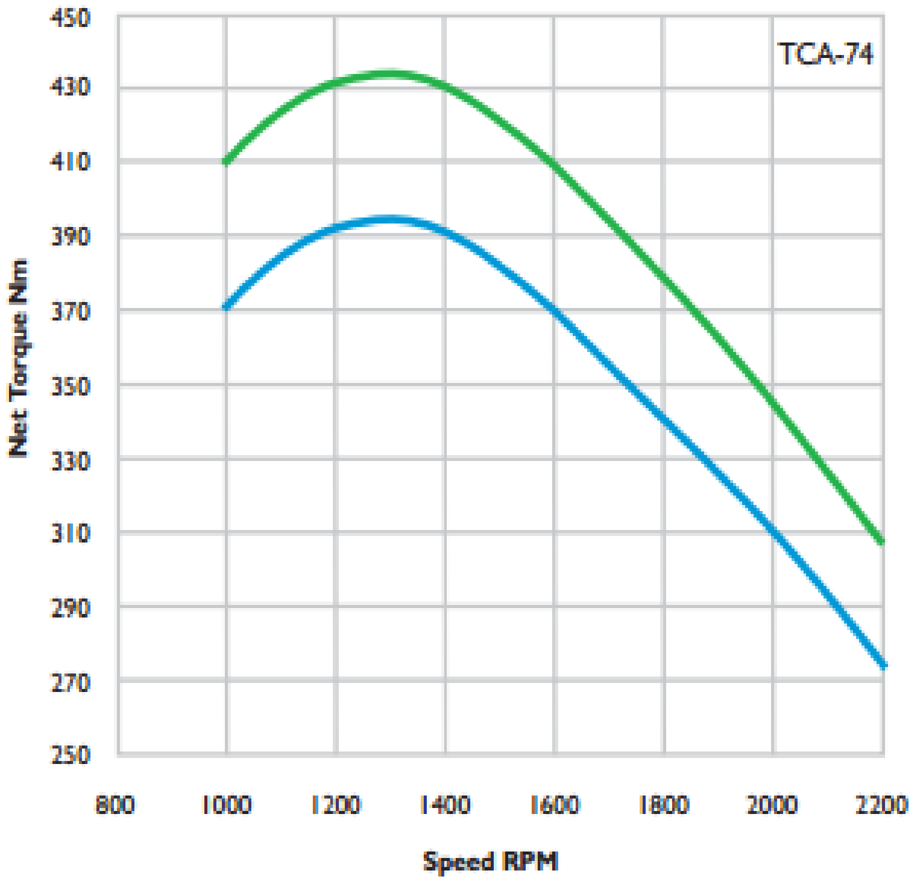
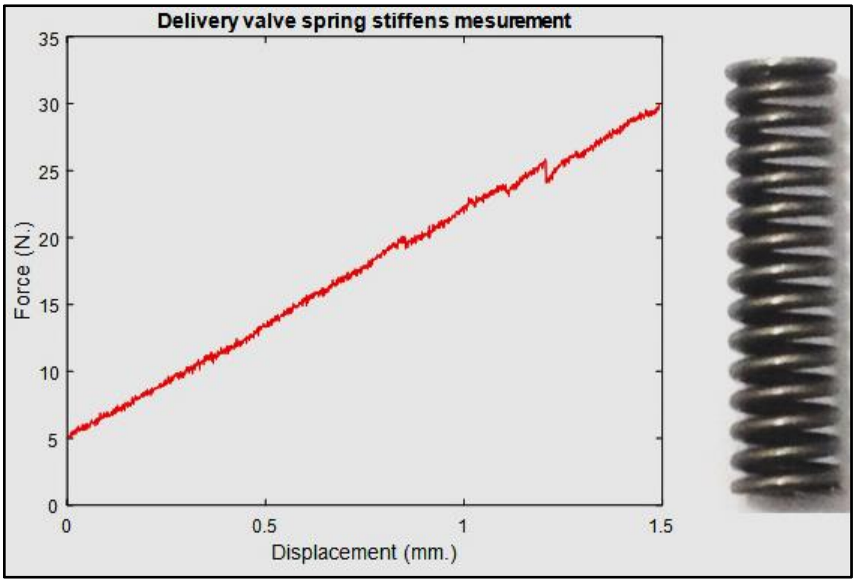


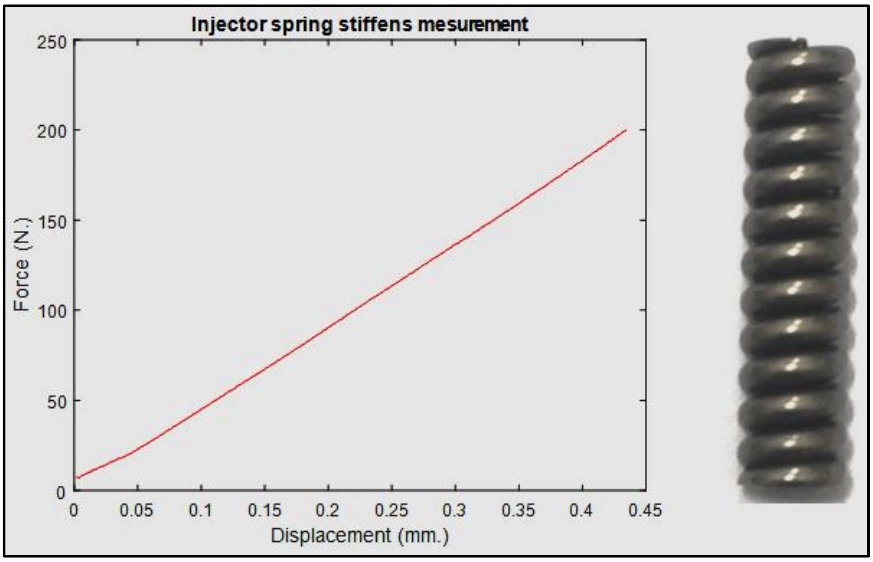
Figure Carve of Engine power

Stiffens Spring Test Measurement of Fuel Delivery Valve and Injector Needle

The important spring in fuel injection system is delivery valve spring and needle valve spring. Instron digital machine have been used to testing the both spring of delivery valve and injector. Clearly result to comparing between stiffens of injector spring and delivery fuel spring. As see Figures below. Injector spring significant strong than delivery fuel valve.



Stiffens of spring delivery valve measurement



Stiffens of spring fuel injector needle measurement

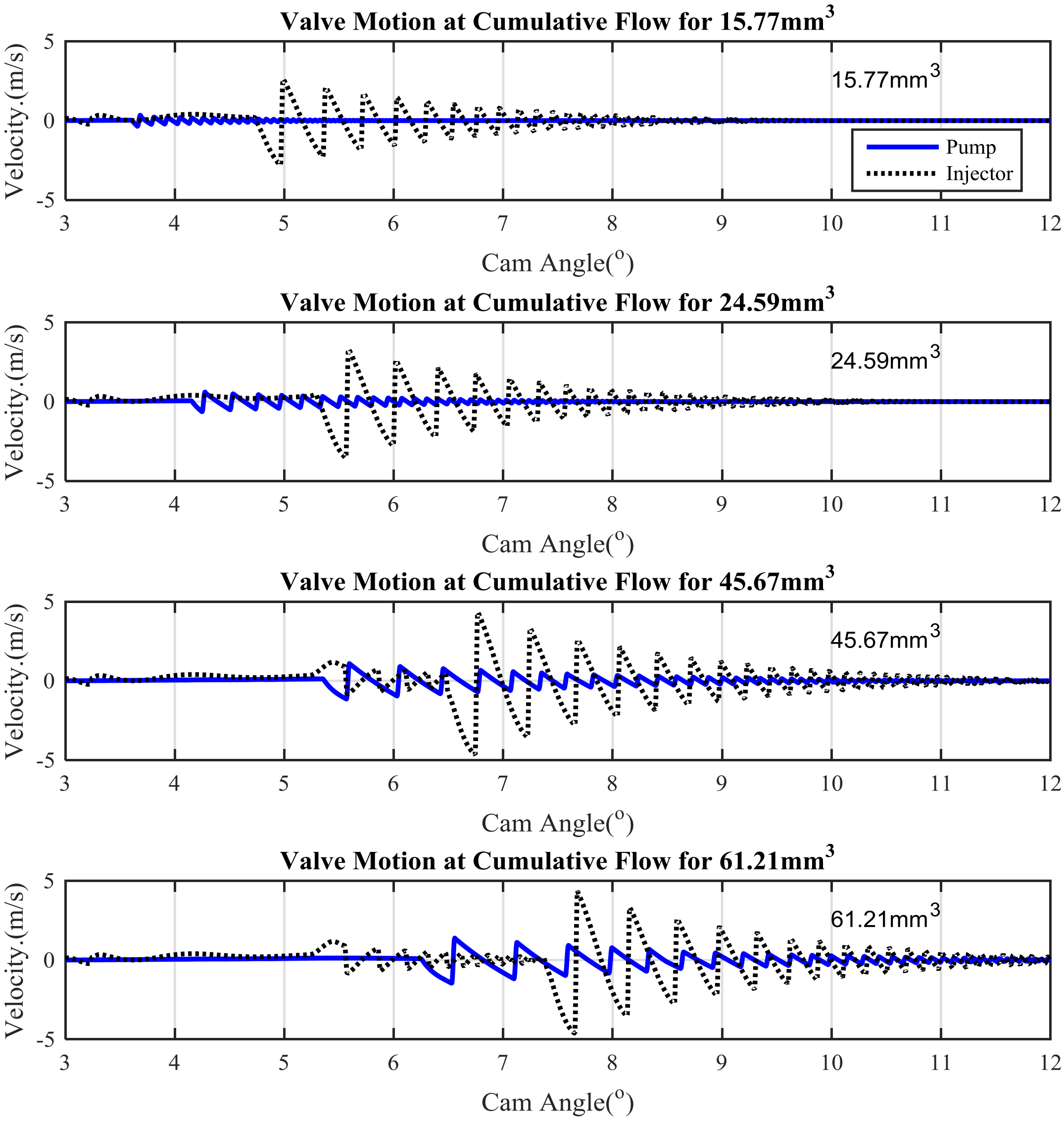
Mathematical model parameters

Fuel pump plunger

Parameters	Equations
Area of plunger	$A_p = (d/2)^2 \pi$
boost stroke	$B_S = (u_{vp}) L_P$
Volume of plunger	$V_P = A_p B_S$
Fuel rate	$Q_P = C_q A_p \sqrt{\frac{2}{\rho}} (P_P - P_0)$
Instantaneous volume	$V_P = 1/2 u_p B_s \pi / u_t \sin(\pi u_m / u_t)$

Valve area	$A_{dv} = (d/2)^2 \pi$
Valve chamber area	$A_{ch} = (d_{ch}/2)^2 \pi$
Delivery valve volume	$V_{dv} = A_{ch} L_{ch}$
effective flow area	$A_{ax} = A_{dv} - d_{dz}(A_{dv} - A_{dvf})/L_m)$
Fuel rate of delivery valve	$Q_{Pd} = C A_{ax} \sqrt{\frac{2}{\rho}} (P_{dv} - P_p)$
Lift velocity	$dy = \left(f_s - k_{ds} d_z - v_c v_{dz} - \left(d_{dz} \max_{dv}\right) k_{dc} v_{dz}\right) / \left(m_{dv}\right)$
Spring force	$f_s = A_{ax} P_{dl}$

Flow rate Injection to engine cylinder	$Q_{ing} = C_q A_{ing} \sqrt{\frac{2}{\rho}} (P_{ing} - P_{cy})$
Lift velocity	$dy = \left(f_{\sin g} - k_n d_n - \left(d_n \max_n\right) k_{nc} v_n\right) / \left(m_n\right)$
Spring force	$f_s = A_n P_n$


Valve Motion at Cumulative Flow for 15.77mm3
15.77mm3
Pump
Injector
Velocity.(m/s)
Cam Angle(o)
Valve Motion at Cumulative Flow for 24.59mm3
24.59mm3
Velocity.(m/s)
Cam Angle(o)
Valve Motion at Cumulative Flow for 45.67mm3
45.67mm3
Velocity.(m/s)
Cam Angle(o)
Valve Motion at Cumulative Flow for 61.21mm3
61.21mm3
Velocity.(m/s)
Cam Angle(o)

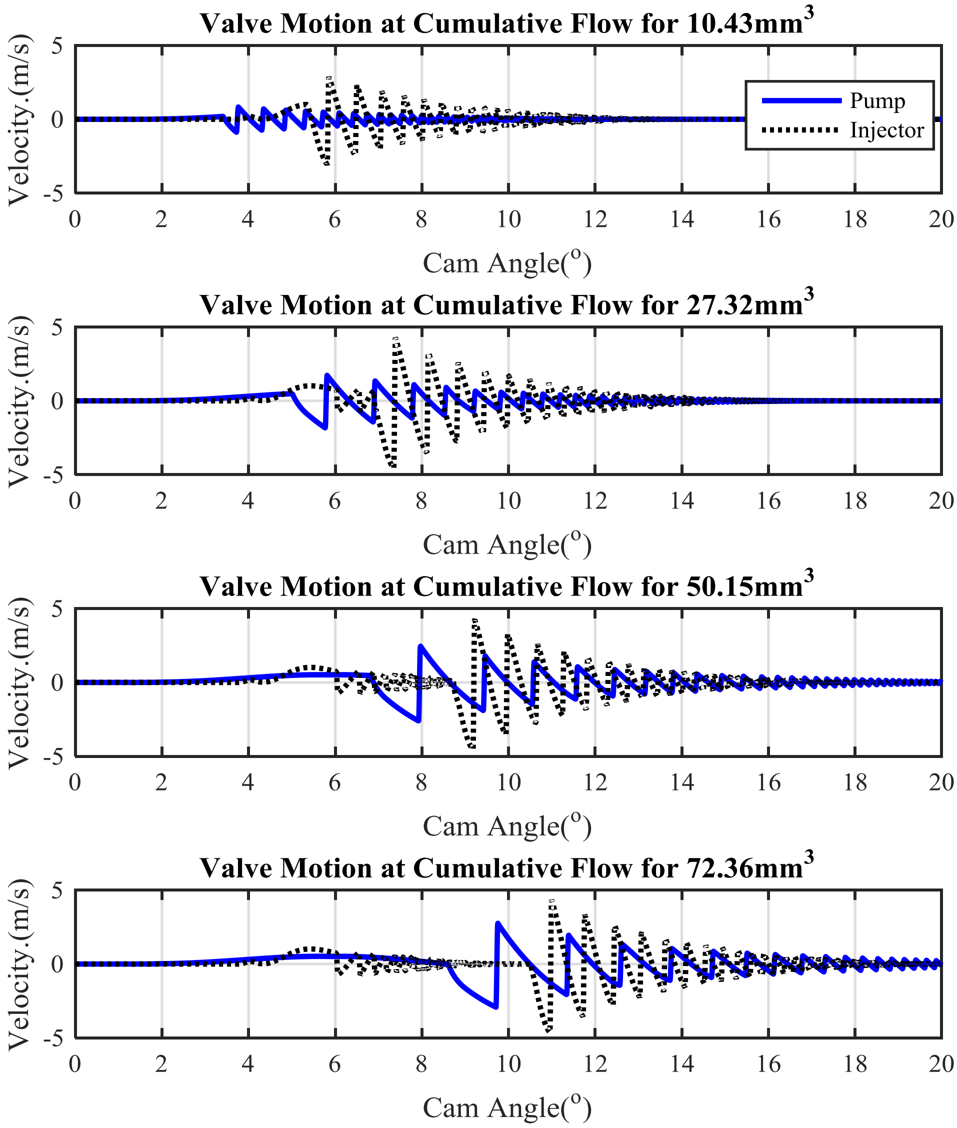
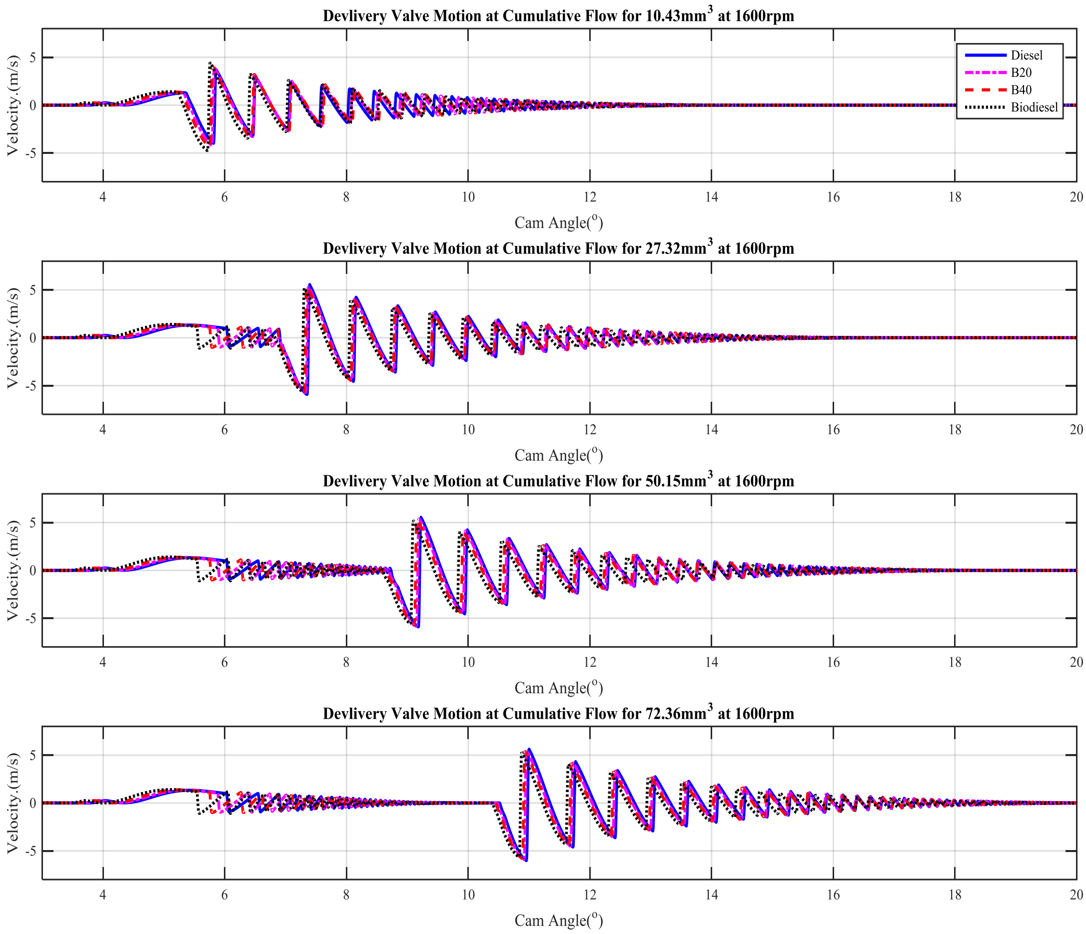


Figure 5-12 Displacement of delivery valve and injector needle valve


Devlivery Valve Motion at Cumulative Flow for 10.43mm3 at 1600rpm
Diesel
B20
B40
Biodiesel
Velocity.(m/s)
Cam Angle(o)
Devlivery Valve Motion at Cumulative Flow for 27.32mm3 at 1600rpm
Velocity.(m/s)
Cam Angle(o)
Devlivery Valve Motion at Cumulative Flow for 50.15mm3 at 1600rpm
Velocity.(m/s)
Cam Angle(o)
Devlivery Valve Motion at Cumulative Flow for 72.36mm3 at 1600rpm
Velocity.(m/s)
Cam Angle(o)

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