

**ÇUKUROVA UNIVERSITY
INSTITUTE OF NATURAL AND APPLIED SCIENCES**

PhD THESIS

Erinç ULUDAMAR

**VIBRATION MEASUREMENT BASED ANALYSES OF INTERNAL
COMBUSTION ENGINES**

DEPARTMENT OF MECHANICAL ENGINEERING

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ÇUKUROVA UNIVERSITY
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ABSTRACT

PhD THESIS

VIBRATION MEASUREMENT BASED ANALYSES OF INTERNAL COMBUSTION ENGINES

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ÇUKUROVA UNIVERSITY
INSTITUTE OF NATURAL AND APPLIED SCIENCES
DEPARTMENT OF MECHANICAL ENGINEERING

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Nowadays automotive manufacturers face a two-fold challenge; on the one hand they have to fulfil the costumer satisfactions; on the other they must decrease the production costs by meeting the many regulations. Due to the depletion of fossil based fuel, alternative fuels have gained great importance in automotive sector in last decades. Therefore all effects of them must be well-known on internal combustion engine.

In this thesis, noise and vibration characteristics of diesel engines fuelled with different alternative fuels have been studied in details.

Throughout the experimental study, three different test rigs were used. At the first rig, the diesel engine was fuelled with low sulphur diesel fuel, sunflower biodiesel, canola biodiesel, and corn biodiesel blends. Engine vibration has been recorded at different engine speeds in order to validation of experiments on other experimental engines. At the second test rig, the diesel engine was additionally fuelled with hydrogen and natural gas additions through the intake air. At this test rig, noise, vibration and emission characteristics were evaluated at various engine speeds. At the last test rig, the same biodiesel blends were used in order to examine their engine combustion characteristic.

The results revealed that biodiesel, hydrogen and natural gas additions lowered the engine block vibration, noise and most of exhaust emissions that of low sulphur diesel fuel.

Key Words: Alternative fuels, Diesel engine, Exhaust emissions, Noise, Vibration

ÖZ

DOKTORA TEZİ

İÇTEN YANMALI MOTORLARDA TİTREŞİM ÖLÇÜM TABANLI ANALİZLER

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Günümüzde, otomotiv sektörü iki sorunla karşı karşıya; bir yandan müşteri memnuniyeti sağlamaya çalışırken; diğer yandan birçok kurala uyarak üretim maliyetlerini azaltmak zorundadırlar. Son on yılda, fosil kaynaklı yakıtlar azalmakta olduğundan dolayı, otomotiv sektörü için alternatif yakıtlar oldukça önem kazanmıştır. Bu yüzden, bu yakıtların içten yanmalı motor üzerindeki bütün etkileri çok iyi bilinmelidir.

Bu tezde, değişik alternatif yakıtlarla beslenen dizel motorların ses ve titreşim karakteristiği detaylı olarak çalışılmıştır.

Deneyisel çalışmalar boyunca üç farklı test düzeneği kullanılmıştır. Birinci düzeneğe dizel motor düşük sülfürlü dizel yakıtı, ayçiçek biyodizeli, kanola biyodizeli ve mısır biyodizeli karışımlarıyla beslenmiştir. Diğer deney motorları üzerindeki deneylerin sağlamasını gerçekleştirmek için bu yakıtların motor üzerindeki titreşimleri değişik motor hızlarında kaydedilmiştir. İkinci test düzeneğinde dizel motoru aynı zamanda emme manifoldundan hidrojen ve doğal gaz verilerek beslenmiştir. Bu test düzeneğinde ses, titreşim ve emisyon karakteri değişik motor hızlarında değerlendirilmiştir. Son test düzeneğinde ise motor yanma karakteristiğini irdelemek için aynı biyodizel karışımları kullanılmıştır.

Sonuçlara göre, düşük sülfür dizel yakıtına göre, biyodizel, hidrojen ve doğal gaz motor blok titreşimini, sesini ve birçok egzoz emisyonunu düşürmüştür.

Anahtar Kelimeler: Alternatif yakıtlar, Dizel motoru, Egzoz emisyonları, Ses, Titreşim

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ABBREVIATIONS

a_{total}	: Total vibration acceleration
B	: Biodiesel
BSFC	: Brake Specific Fuel Consumption
CaB100	: Pure Canola Biodiesel
CaB20	: 20% Canola Biodiesel and 80% Low Sulphur Diesel Fuel
CaB40	: 40% Canola Biodiesel and 60% Low Sulphur Diesel Fuel
CaB60	: 60% Canola Biodiesel and 40% Low Sulphur Diesel Fuel
CaB80	: 80% Canola Biodiesel and 20% Low Sulphur Diesel Fuel
CI	: Compression Ignition
CNG/NG	Compressed Natural Gas
CNG0	: Without Compressed Natural Gas Addition
CNG10	: 10 l/min Compressed Natural Gas Addition
CNG15	: 15 l/min Compressed Natural Gas Addition
CNG5	: 5 l/min Compressed Natural Gas Addition
CO	: Carbon Monoxide
CO ₂	: Carbon Dioxide
CoB100	: Pure Corn Biodiesel
CoB20	: 20% Corn Biodiesel and 80% Low Sulphur Diesel Fuel
CoB40	: 40% Corn Biodiesel and 60% Low Sulphur Diesel Fuel
CoB60	: 60% Corn Biodiesel and 40% Low Sulphur Diesel Fuel
CoB80	: 80% Corn Biodiesel and 20% Low Sulphur Diesel Fuel
CR	: Compression Ratio
D100	: Pure Low Sulphur Diesel Fuel
dB	: Decibel
DFT	: Discrete Fourier transform
FFT	: Fast Fourier Transform
H0	: Without Hydrogen Addition
H ₂	: Hydrogen Gas
H3	: 3 l/min Hydrogen Addition

H6	: 6 l/min Hydrogen Addition
HC	: Hydrocarbons
IC	: Internal Combustion
NO _x	: Nitrogen Oxide
PM	: Particulate matter
RMA	: Root Mean Square
SB100	: Pure Soybean Biodiesel
SB20	: 20% Soybean Biodiesel and 80% Low Sulphur Diesel Fuel
SB40	: 40% Soybean Biodiesel and 60% Low Sulphur Diesel Fuel
SB60	: 60% Soybean Biodiesel and 40% Low Sulphur Diesel Fuel
SB80	: 80% Soybean Biodiesel and 20% Low Sulphur Diesel Fuel
SI	: Spark Ignition
SO ₂	: Sulphur dioxide
SPL	: Sound Pressure Level

1. INTRODUCTION

Energy, which is a property of objects, is essential for whole universe. In our world, it is necessary for sustain living systems. Since eighteenth century energy potential of human labour replace with fossil fuels such as petroleum, natural gas and coal to support agricultural and industrial productivity (Brook et al., 2014). Unfortunately their natural resources are finite (Speirs et al., 2015; Chiari and Zecca, 2011).

Spark ignition (SI) and compression ignition (CI) are the common engines that use in vehicles to convert fuel's chemical energy to mechanical energy. Moreover CI engines are widely used as power sources in medium and heavy duty application. Thus, they have been dominating the world since it was introduced by Rudolf Diesel in 1910 (Kaimal and Vijayabalan, 2015). The main advantages of CI engines are its high thermal efficiency, simplicity, durability and robust construction (Rashed et al., 2016; Banerjee et al., 2015). Unfortunately they come up with some important problems such as noise and exhaust emissions that harmful for environment, and vibration (Ipci and Karabulut, 2015). In the last two decades, researchers work on alternatives to conventional diesel fuel have advanced significantly. Biofuel is the most prominence alternative fuel basically due to its advantages such as, renewable, non-toxic, and biodegradable (Millo et al., 2015).

Many countries are mandate by legislations and support the interest in biofuels. The aim of European Union countries is to get %10 of the transport fuel of every European Union country from renewable sources whereas China was set a target to meet 15% of transport energy from biofuels by 2020 (Sukkasi et al., 2010; Roy et al., 2013). Furthermore Canada, Colombia, India, Thailand, and the United States have adopted new targets, some mandatory, for increasing the contribution of biofuels (Kojima and Johnson, 2006). For internal combustion engines, biofuels are used in liquid form as biodiesel and bio-ethanol or in gaseous form as hydrogen and biogas (Khiari et al., 2016; Vallinayagam et al., 2014).

Biodiesel (fatty acid methyl esters) is oxygenated fuel consisting of long chain fatty acids derived from vegetable oil or animal fat (Mofijur et al., 2016; Arbab

et al., 2013; Zhang et al., 2015; Alptekin et al., 2015). Globally, researchers attempt to develop and improve vegetable oil properties in order to approximate the properties of conventional diesel fuels. Pyrolysis (thermal cracking), dilution, micro-emulsion, and transesterification are the main biodiesel production technologies to solve the problems (Atabani et al., 2012; Balat and Balat, 2010). Recently, the usage amount of biodiesel dramatically increases due to reduction of unburned hydrocarbons (HC), particulate matter (PM), carbon monoxide (CO), sulphur dioxide (SO₂), and polycyclic aromatic hydrocarbons engine emissions and ease of production (Bergthorson and Thomson, 2015; Talebian-Kiakalaieh et al., 2013). Furthermore little or no engine modification is necessary to use it in CI engines (Özener et al., 2014). However higher viscosity and nitrogen oxide (NO_x) emission increment compared to conventional diesel fuel are the disadvantages of biodiesels (Rocabruno-Valdés et al., 2015; Ramirez Verduzco, 2013). In Table 1.1 advantages and disadvantages of biodiesel according to conventional diesel fuel were given in details.

Table 1.1. Advantages and disadvantages of biodiesel compared to conventional diesel fuel

Advantages	Disadvantages
- Higher viscosity which increases it's lubricity properties - High nontoxicity and biodegradability implies less impact on environment pollution - Low sulphur content and no aromatic components results low PM, SO₂ and HC - Safer to handle, store, and transport as high flash point	- Higher production cost, limited feedstock availability - Produces higher NO_x emissions in unmodified diesel engine - Coking, filter plugging, auto-oxidation, corrosive nature - Most of the biodiesel feedstock's are from edible source results increase the price of food - Higher BSFC due to lower heating value. Higher density and viscosity of biodiesel leads to poor atomization

The researchers worked with natural gas (NG) in diesel engine found out that it provides to reduce NO_x emissions quite opposite of biodiesel addition (Papagiannakis and Hountalas, 2003; Papagiannakis and Hountalas, 2004; Liu et al., 2013; Engerer and Horn, 2010). Thus, many studies were conducted on biodiesel blends with NG addition into the engine (Ryu, 2013a, Gharehghani et al., 2015, Tarabet et al., 2014). NG has become a promising automotive fuel due to its rich reserves and clean emissions (Wang et al., 2016). Previous studies showed that NG can be used successfully in SI engines because of its fuel properties are similar to those of gasoline fuel. Since CI engines have higher compression ratios than SI engines, NG does not autoignite under compression alone with typical CI engine compression ratios; therefore it is used to power CI engines via the dual-fuel mode, where a high-cetane fuel is injected along with the NG in order to provide a source of ignition for the charge (Li et al., 2016).

Hydrogen (H_2) is another gas that has been widely investigated for fuelling CI engines (Zhou et al., 2016). In comparison to NG, H_2 has the advantage of renewable, recyclable, and promising long term fuel (Parthasarathy et al., in press). Moreover, carbon atom free structure of H_2 only reveals water after burning period and this specialty puts H_2 forward in alternative fuel types (Karagöz et al., 2015a). H_2 can be used as a sole fuel in SI engine, either by carburetion or by direct injection however, in a CI engine, it cannot be directly used due to its higher self-ignition temperature (Yılmaz, 2010). Therefore, diesel fuel can be used as a pilot fuel to ignite H_2 . Properties of diesel fuel, NG and H_2 are given in Table 1.2.

Table 1.2. Comparison of diesel, hydrogen and natural gas

Properties	Diesel	Hydrogen	Natural Gas
Main component	C ₁₂ H ₂₃	H ₂	Methane (CH ₄)
Auto-ignition temperature (K)	553	858	923
Lower heating value (MJ/kg)	42,5	119,93	50
Density (kg/m ³)	833–881	0,08	0,862
Molecular weight (g/mol)	170	2,016	16,043
Flammability limits in air (vol%) (LFL–UFL)	0,7–5	4–75	5–15
Flame velocity (m/s)	0,3	2,65–3,25	0,45
Specific gravity	0,83	0,091	0,55
Boiling point (K)	453–653	20.2	111,5
Cetane number	40–60	-	-
Octane number	30	130	120
Diffusivity in air (cm ² /s)	-	0,61	0,16
Min ignition energy (mJ)	-	0,02	0,28

Dynamic and challenges in market of automotive industry enforces manufacturer to deal with alternative fuels. The companies which do not follow new trends in industry will have to stay behind in the market thus; automotive manufacturers continuously have to develop their product due to high costumer demands and competition in sector (Atalay et al., 2013; Holm et al., 2014). Comfort is one of the crucial point for costumer to choose a vehicle. Hence, driving comfort is one of the most important issues in vehicle development. Vehicle companies are trade-off driving comfort and expenditures of their products. Since the engine itself is a significant source of vibration and noise considerable attention should be paid on the effect of alternative fuels on engines.

Vibration is the repetitive, periodic or oscillatory response of a mechanical system (Silva, 2007). Vibration occurs when a system is displaced from position of stable equilibrium. The system tends to return to this equilibrium position under the action of restoring forces such as elastic or gravitational forces (Dukkipati, 2006). In

mechanical systems, rotary motion is the most common periodic phenomena. Mechanical vibration is sometimes an undesirable results of imperfections associated with the design, manufacturing, or operation of mechanical devices and systems, such as the vibration associated with the unbalanced masses of rotating or reciprocating machines (Dimarogonas, 1992).

In vehicles, engines can generate disturbing forces at different frequencies and causes passenger discomfort. Secondary sources such as the ventilation system, pumps and circulation systems are swamped by the effect of the engine (Plint, 2001). An engine may be regarded as having six degrees of freedom of vibration about orthogonal axes through its centre of gravity. These are linear vibrations along each axis and rotations about each axis.

The acceptable level of vibration on a machine or structure is determined by its acceptability to the operating personnel and by the ability of the machinery, equipment and structure to carry the vibration without damage or failure. The equation of the level of vibration that can be endured by human beings without annoyance, loss of efficiency, or physical damage has been studied widely (Dimarogonas, 1992). Recommendation of International Standards Organization Technical Committee (ISO/TC 108 – Mechanical vibration and Shock) and acceptable vertical vibration levels on standing and sitting human beings are illustrated in Figure 1.1 and figure 1.2, respectively in the terms of root mean square (RMS) acceleration level which produce equal fatigue-decreased proficiency. Exceeding the exposure specified by the curves will, in most situations cause noticeable fatigue and decreased job proficiency in most tasks (Brüel and Kjaer, 1984).

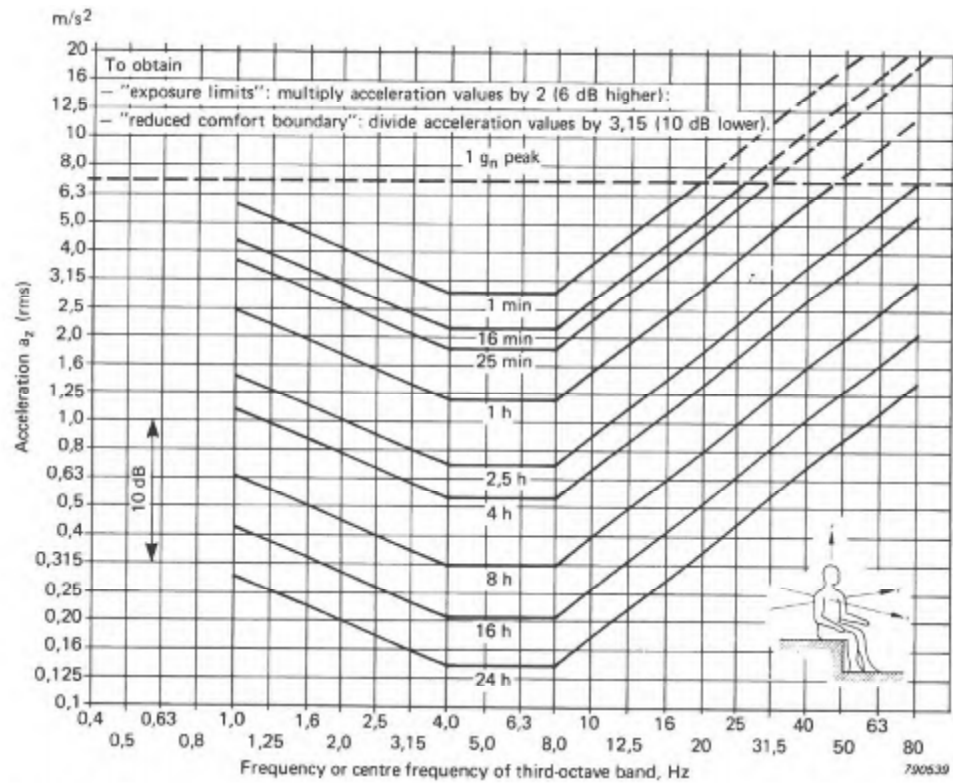


Figure 1.1. ISO suggested acceptable vertical vibration levels

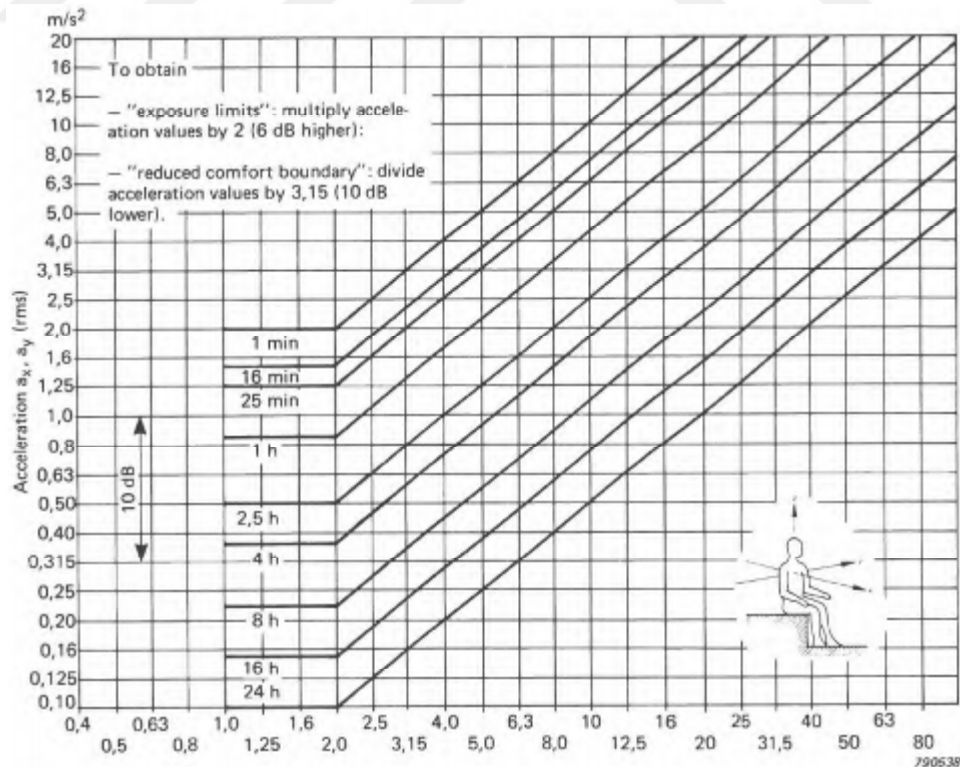


Figure 1.2. ISO suggested acceptable horizontal vibration levels

Another issue that affect the vehicle comfort is the noise generation of the engine. Furthermore, they cause noise emission for the environment. According to the World Health Organization, more than one million healthy life years are lost every year in western European cities due to noise (Giakoumis et al., 2016). Therefore, some countries have introduced regulations regarding maximum noise emissions of road vehicles. The regulations are generally coordinated internationally, both with regard to measuring methods and, to some degree, with respect to noise limits. The European Union and United Nations Economic Commission for Europe countries use of the standardized method for measuring the noise emissions of individual vehicles that is most widely accepted is described in the International Standard ISO 362 (Acoustics - Measurement of noise emitted by accelerating road vehicles) whereas, Japan and USA have slightly different regulations, with respect to each other and to Europe (noise emissions of road vehicles).

In this thesis, vibration and noise effect of different alternative fuel to conventional diesel fuel was investigated on three different engines. Sunflower, canola and corn biodiesel blends were prepared to fuel the engines. Furthermore, hydrogen and natural gas were injected though intake manifold of a test engine. carbon monoxide (CO), carbon dioxide (CO₂) and nitrogen oxide (NO_x) emission characteristic of alternative fuels were also presented. Then linear and non-linear based regression analysis based model was developed to predict the relationship between fuel properties and noise-vibration of the engine with excellent agreement.



2. PRELIMINARY WORK

In literature, there are many studies about performance and emission characteristic of biodiesels from various feedstock. Results of some studies about performance, combustion and emission characteristics of various biodiesels were given in Table 2.1.

Table 2.1. Previous studies about combustion, performance and emission characteristic of diesel engines fuelled with various biodiesels

Reference	Feedstock of Biodiesel and Its Blend Proportion with Diesel Fuel	Engine and Operating Condition	Engine Performance and Combustion	Emissions
Lešnik and Biluš, 2016	Rapeseed %25 %50 %75 %100	6 cylinders (C) natural aspirated (NA), water cooled (W), diesel engine 1360, 1700, and 2000 rpm on full throttle positions	Reduction of torque Increase of brake specific fuel consumption	Reduction of NO _x and CO emission
Ali et al., 2016	Palm 10%, 20%, 30%, 40%, 50%	NA W 4-C diesel engine at 2500 rpm with 50% open throttle.	Reduced the engine brake power Increased the brake specific fuel consumption, No significant difference for the engine brake thermal efficiency	-

Table 2.2. Continue

Can, 2014	Waste Cooking 5% and 10%	NA, 1-C, diesel engine under four different engine loads (BMEP 0.48–0.36–0.24–0.12 MPa) and 2200 rpm engine speed	Injection delay decreased	CO ₂ emissions slightly increased
			Maximum heat release rate and in-cylinder pressure rise rate were slightly decreased	No significant changes on CO emissions at the low and medium loads, while significant improvements up to 51% at the full load
Tüccar et al., 2014	Citrus Sinensis 5%, 10% and 20%	NA, 4-C, diesel engine Between 1000 and 2400 rpm engine speed range at full load condition	A slightly increment on BSFC (up to 4%) and some reduction on BTE (up to 2.8%)	THC emissions showed the decreased trend up to 5% for low and medium engine loads and up to 29% for the high engine load
				NO _x emissions increased up to 8.7% while smoke emissions decreased
Pali et al., 2015	Sal seed oil 10%, 20%, 30% 40%	W, 1-C diesel engine 1500 rpm at different loads	BTE dropped marginally	CO, UHC and smoke emissions lowered NO _x emissions increased

Table 2.3. Continue

Sakthivel et al., 2014	Fish oil %20, %40, %60, %80, %100	1-C, A/C Diesel engine 1500 rpm at different loads	Mean brake thermal efficiency decreases Ignition delay is shorter Peak pressure and rate of pressure rise are lower Biodiesel produces lower heat release rates	HC and CO emissions decrease by 21% CO ₂ emission slightly increase by 1.2% NO _x decrease by 2.3%
Rahman et al., 2014	Jatropha 10% and 20%	4-C Diesel engine (1000 RPM 10% load, 1200 RPM 12% load and 1500 RPM 15% load	Brake specific fuel consumption increased	CO emissions decreased HC emissions decreased increase of NO _x emission
Behçet et al., 2015	Chicken oil 20%	1-C, A/C diesel engine at different speeds under full load	Brake power, torque values decreased BSFC values increased	CO, UHC and CO ₂ concentrations of blended fuels decreased while the NO _x concentration increased NO _x emission increased by 6,3%
Uludamar et al., 2015	Soybean %20	W/C, 4-C diesel engine between 1000 and 2400 rpm engine speed range at full load condition	Torque values reduced by 4,7% Brake specific fuel increased 6,1%,	Average reduction of CO emissions were 10,4% smoke opacity emission reduced 1,4%,

Performance, combustion, and emission characteristics of diesel engines fuelled with NG and H₂ gases were also studied by some researchers as well.

Since NG is a clean burning fuel as compared to the conventional liquid fuels like diesel or gasoline it is a prominence fuel to eliminate some adverse effect of diesel engines such as its high NO_x emissions, some researchers were studied with NG. Abagnale et al. (2014) presented a paper which investigated the effect of different fuel ratios on the performance and emission levels of a common rail diesel engine fuelled with CNG and diesel fuel as experimentally and numerically whereas Selim (2001) was measured and analysed the pressure rise rate at different engine loads, engine crankshaft speeds, pilot injection angle, and different pilot mass quantity of a single cylinder variable compression indirect injection diesel engine. Poompipatpong and Cheenkachorn (2011) was modified a diesel engine for CNG operation in order to optimize its performance. They changed the compression ratio (CR) of the engine as 9.0:1, 9.5:1, 10.0:1 and 10.5:1 when they used CNG as the main fuel. The engine was operated between 1000 and 4000 rpm to utilize the performance and emission. Papagiannakis et al. (2010) conducted an experimental study to examine the effect of the total air/fuel ratio on various parameters. They found out that the decrease of the total relative air/fuel ratio caused to a lower brake thermal efficiency compared to diesel operation and dual fuel operation leads to a decrease of soot and NO_x emissions however HC and CO emissions were adversely effected. Roy et al. (2014) modelled the performance and emission parameters of a single cylinder four-stroke diesel engine which is fuelled with CNG and diesel by using Artificial Neural Network.

Some researchers are fuelled their engine with also biodiesel beside CNG and diesel. Gharehghani et al. (2015) used waste fish oil whereas Tarabet et al. (2014) used eucalyptus biodiesel in engine experiments. Ryu (2013) used biodiesel that produced from edible frying oils as a pilot injector to ignite CNG. The aim was to investigation of pilot injection pressure on engine performance and exhaust emissions. Paul et al. (2014) are another research group who presented a paper about the performance of a diesel engine run with biodiesel and diesel as pilot fuel with CNG as the primary fuel. They used Pongamia pinnata methyl ester (PPME) as a

biodiesel. They concluded that PPME-CNG dual fuel operation is more effective than Diesel-CNG dual fuel operation in improving the performance and emission characteristics of the engine.

The effect of H_2 gas in a diesel engine was also studied by many researchers due to it is a long-term renewable and least polluting fuel among various alternative fuels for internal combustion (IC) engines.

Karagöz et al., (2015b) injected hydrogen fuel into intake manifold using an LPG-CNG injector that is controlled by a self-developed ECU, whereas diesel fuel was directly injected into cylinder using diesel injector. They used 0%, 22%, and 53% hydrogen energy fractions at 1100 rpm constant engine speed and full load. According to their results, they found out that improvement of CO and smoke emissions whereas, THC emissions raised. On the other hand, a slight increase was observed with 22% hydrogen and a dramatic increase with 53% hydrogen addition in NO_x emissions compared with pure diesel fuel (0% hydrogen). Also, peak-in-cylinder pressure values increased by 7,81% and 36,2% with 22% and 53% hydrogen addition, respectively, in comparison to pure diesel fuel. Furthermore, a 25,77% increase in peak heat release rate was obtained with 22% hydrogen addition and a great increase of 110,94% was acquired with 53% hydrogen enrichment. At another study of Karagöz et al. (2015c), they stabilized hydrogen energy fractions at 1100 rpm in different engine loads. Quadri et al., (2015) induced 10% and 20% of hydrogen by mass of fuel into the combustion chamber in conjunction with air in hydrogen-diesel dual fuel mode. They conducted the experiment at three different operation pressure; 200, 220, and 240 bars at full load condition in order to observe its effect on performance, emission, rate of heat release and rate of pressure release. Köse and Ciniviz (2013) presented a study that about hydrogen effect on performance and exhaust emissions parameters of a compression ignition engine operated at various engine speed and full load conditions. The engine fuelled with diesel fuel while hydrogen was added to inlet manifold at rates of 2.5%, 5% and 7.5% as volume. As a result, an increase in engine torque, power, thermal efficiency, NO_x and exhaust gas temperature were acquired at every hydrogen addition ratio while a decrease in HC, CO and oxygen (O_2) emissions were attained. Zhou et al.

(2013) fuelled the engine with ultra-low sulphur diesel (ULSD), palm methyl ester (PME), a blended fuel containing 50% by volume each of the ULSD and PME with hydrogen addition of the total fuel energy by 10% and 20%, at an engine speed of 1800 rpm and under five loads.

They concluded that there is little change in peak in-cylinder pressure and peak heat release rate. The influence on fuel consumption and brake thermal efficiency was engine load and fuel dependent; being negative for the three liquid fuels at low engine loads but positive for ULSD and B50 and negligible for PME at medium-to-high loads. CO and CO₂ emissions decreased while HC decreased at medium-to-high loads, but increases at low loads. NO_x emission increased for PME only but NO₂ increased for the three liquid fuels. Smoke opacity, particle mass and number concentrations were all reduced for the three liquid fuels. Zhou et al. (2014) investigated the combustion and emission characteristics of a diesel engine with addition of hydrogen or methane for dual-fuel operation, and mixtures of hydrogen and methane for tri-fuel operation

Engine vibration characteristic by using biofuels is recently become popular. Few studies were investigated in this field.

How et al. (2014) investigated on combustion, vibration characteristics, performance and emissions of a high pressured common rail diesel engine which is fuelled with four different coconut biodiesel blends (B10, B20, B30 and B50). The test engine operated under 0,17, 0,34, 0,52, 0,69 and 0,86 MPa loads. As a result, they found out that brake specific fuel consumption and brake specific energy consumption were influenced significantly by biodiesel fuel blends at all engine loads. Coconut biodiesel blends were reduced CO and smoke emissions regardless of the load conditions. Also, at all load condition they observed that shorter ignition delay and longer combustion duration has occurred with the use of biodiesel blends and the vibration results showed that the largest reduction of 13,7% in RMS (root mean square) of acceleration was obtained with B50 at engine load of 0.86 MPa with respect to the baseline diesel. Gravalos et al. (2013) presented a paper about vibration behaviour of a spark engine fuelled with unleaded gasoline, ethanol blends and methanol blends. Blends were prepared as 10%, 20%, and 30% volume percentages.

They tested the engine at 1000, 1300, 1600 and 1900 rpm. The experimental results showed that the vibration amplitude produced by the gasoline fuel was higher at low frequencies around 1500 Hz. On the contrary, the vibration amplitude generated by the gasoline-methanol blend had a high frequency content around 2400 Hz and the gasoline-ethanol blend gave intermediate results at both frequencies. Taghizadeh-Alisaraei et al. (2012) studied vibration of biodiesel and its blends on four- stroke six cylinders diesel engine at different rpms. The magnitude of vibration is measured before and after servicing the engine and they found as 35,11 and 26,21 m/s^2 respectively. It observed by the experiment that vibration magnitude was the least at B20 and B40, although the most at B15, B30, B50 biodiesel blends.

Some studies conducted on engine sound. Redel-Macías et. al. (2014) studied on an engine that is fuelled with biodiesel and diesel fuel blends to measure sound quality. In order to succeed this, they prepared a tractor cabin mock-up. As a result, they developed a model to predict loudness and roughness by considering biodiesel properties. At another study of Redel-Macías et. al. (2012) fuelled their test engine with pomace oil methyl ester (OPME). They considered loudness, sharpness and roughness psychoacoustic metrics to evaluate the noise emission in a receptor position. They found out that biodiesel as partial diesel fuel improved the sound quality. Liu et al. (2008) presented a paper about separating the vibration sources by blind source separation techniques. They combined blind least mean square algorithm and deflation method to separate vibration sources of internal combustion engines. Geng et al. (2003) developed an analytical model of the non-stationary engine vibration considering its time varying transfer properties after analysed the impact excitations of the engine. Junhong and Jun (2006) simulated dynamic and acoustic behaviour of engine with the aid of CAE. Ipci and Karabulut, (2015) investigated the thermal efficiency, knocking, vibration, torque and emission characteristic of a single cylinder, four stroke diesel engine by a heat release rate profile.



3. NOISE AND VIBRATION

Vibrations are the oscillations of a system about an equilibrium position. Vibrations are generally undesirable in machines and structures because they produce increased stresses, energy losses, cause added wear, increase bearing loads, induce fatigue, create passenger discomfort in vehicles, and absorb energy from the system (Dukkipati, 2006). The oscillations may be periodic (such as motion of a pendulum), transient (such as the impact response of vehicle collision), or random (such as the movement of a tire on a gravel road). In Figure 3.1 response of a flying airplane due to certain excitations was shown. The airplane will be excited by flowing air and its wings will vibrate randomly. Because of uncertainty with how air flows, at a deterministic time point. However its engine is working at a certain rotational speed, the corresponding vibration is mainly periodic (Liang and Lee, 2015).

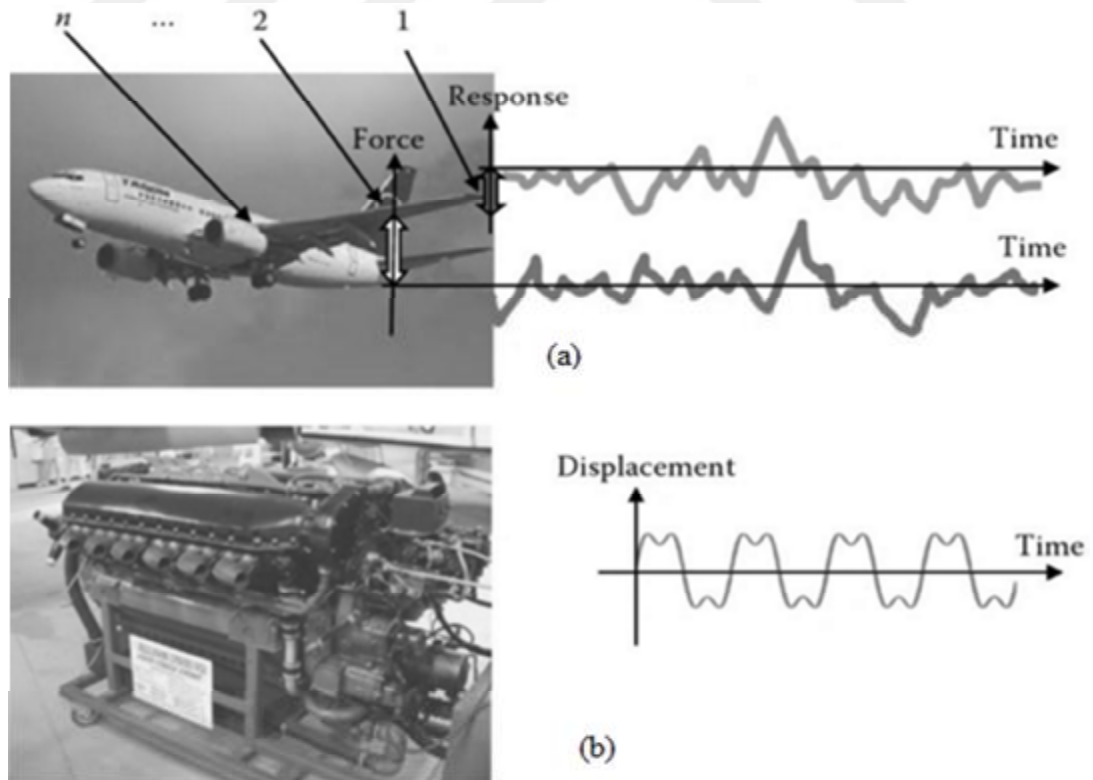


Figure 3.1. Different types of vibration (a) random vibration of airplane wings, (b) periodic vibration of airplane engine.

In mechanical engineering, periodic phenomena are most common due to the rotary motion, which is a periodic motion inherent in most machines. Such motion is repeated during every revolution of the machine and gives rise to many interesting periodic phenomena related to the operation of the machine. Moreover, periodicity is convenient in developing the geometric form of many repeated geometrical features in machines, such as in gear teeth, bolt threads, chain links, fluid machinery (pumps, fans, turbines, blowers) blades, rotary and straight-cutting tools in manufacturing, and so on. Reciprocating machinery, such as piston engines and pumps, reciprocating machine tools, and so on, also have periodic motion (Dimarogonas, 1992).

Vibrations are categorized by the number of degrees of freedom necessary for their modelling, the type of forcing they are subject to, and the assumptions used in the modelling. Vibrations of systems that have a finite number of degrees of freedom are called discrete systems. A system with one degree of freedom is called a single degree-of-freedom system whereas a system with two or more degree of freedom is called a multiple degree-of-freedom system. A system with an infinite number of degrees of freedom is called a continuous system or distributed parameter system. If the vibrations are initiated by an initial energy present in the system and no other source is presented, the resulting vibrations are called free vibrations. If the vibrations are caused by an external force or motion, the vibrations are called forced vibrations. If the vibrations are assumed to have no source of energy dissipation, they are called undamped. If a dissipation source is present, the vibrations are called damped and are further characterized by the form of damping. If the behaviour of all the basic elements are linear, then the vibration is called as linear vibration. If any elements behave non-linearly, then the vibration is called as non-linear vibration (Kelly, 2012).

Vibration and noise signals of machines, engines and structures contain a great deal of dynamic information related to the various exciting forces applied to them and the condition of the system (Dimarogonas, 1992). The response of vibrating system, in general, depends upon external excitations and system parameters (mass, stiffness, and damp). Complex behaviour of the vibrating system can be determined by a simplified mathematical model of the physical system.

Analysis of the physical system may be summarized by mathematical model, formulation of the governing equations, mathematical solution of the equations and their physical interpretation. In Figure 3.2 a model of internal combustion engine test rig was illustrated and its two degree of freedom model was shown in figure 3.3 and its formula given in equation 3.1 and 3.2. Figure 3.4 illustrates the Simulink model.

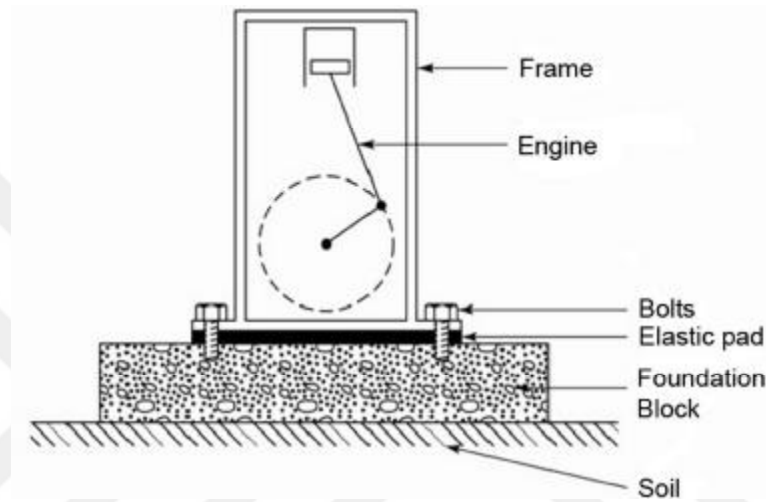


Figure 3.2. Internal combustion engine test rig

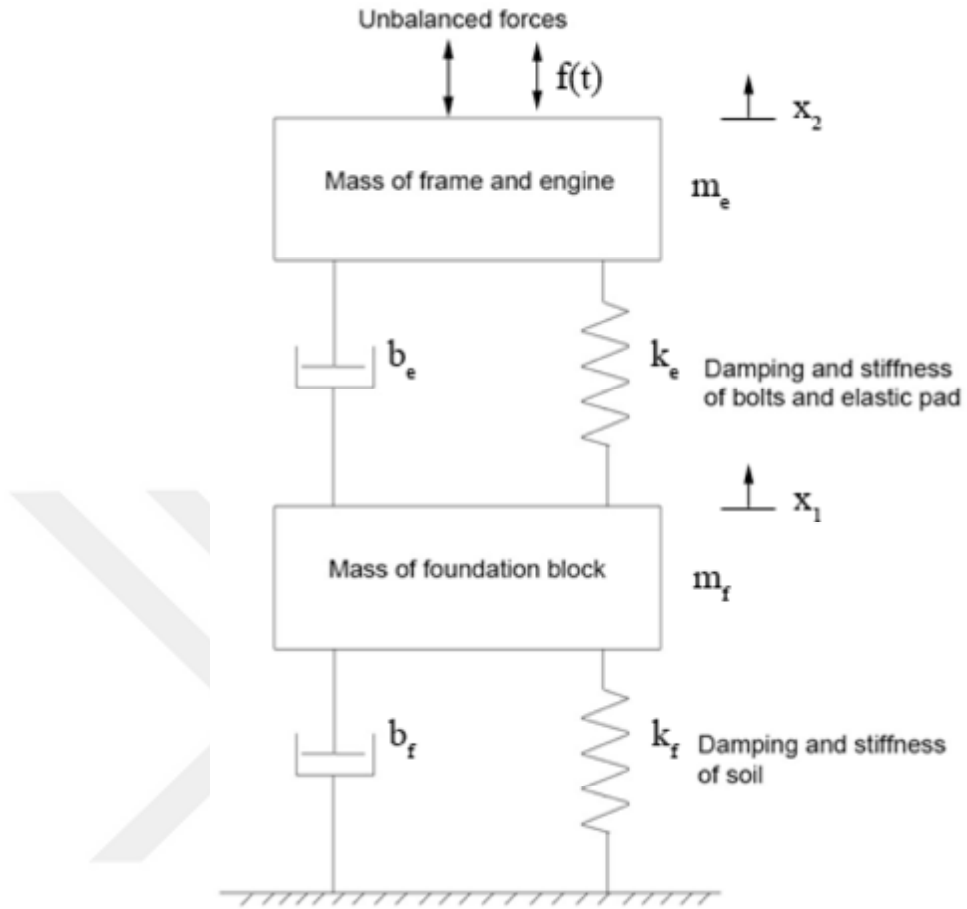


Figure 3.3. Two degree of freedom model of the test rig

$$\ddot{x}_1 m_f = b_f \dot{x}_1 + k_f x_1 - b_e (\dot{x}_2 - \dot{x}_1) - k_e (x_2 - x_1) \quad (3.1.)$$

$$\ddot{x}_2 m_e = b_e (\dot{x}_2 - \dot{x}_1) + k_e (x_2 - x_1) - f(t) \quad (3.2.)$$

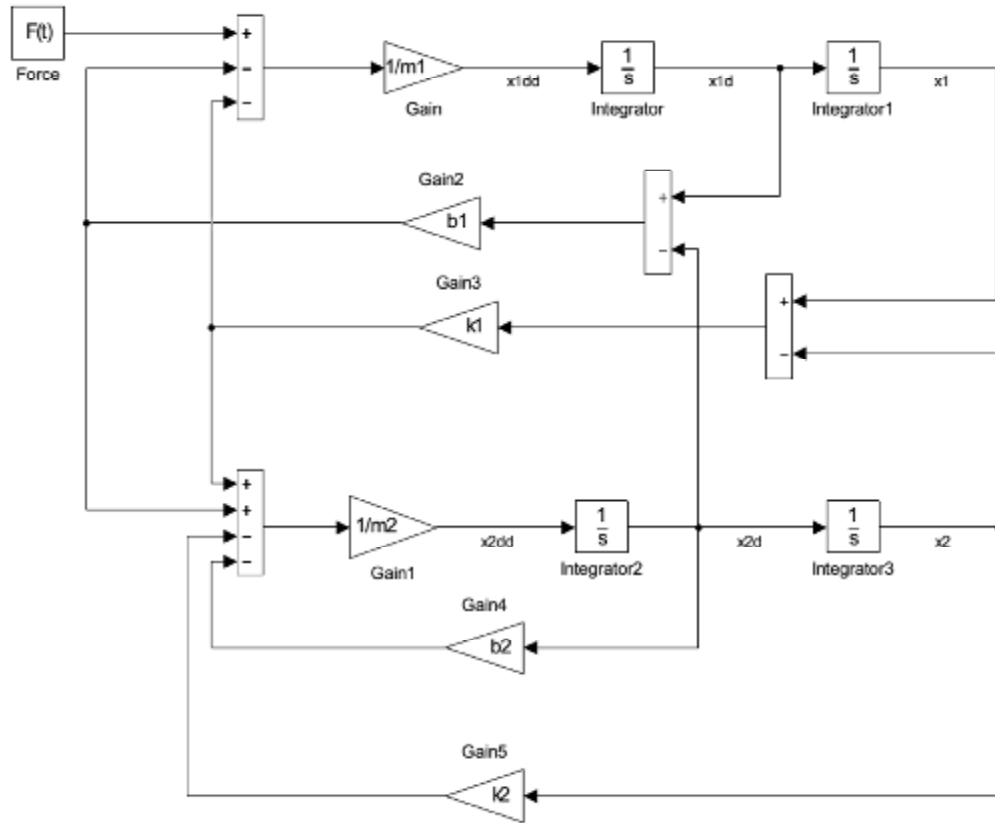


Figure 3.4. Simulink model

Engine itself is almost the only vibration and noise source in a test cell. Secondary sources such as the ventilation system, pumps and circulation systems or the dynamometer are usually swamped by the effects of the engine. Some considerations must be taken into account in the test cell such as:

- The engine must be mounted in such a way that neither it nor connections to it can be damaged by excessive movement or excessive constraint.
- Transmission of engine induced vibration to the cell structure or to other buildings must be controlled.
- Excessive noise levels in the cell should avoided as far as possible and the design of alarm signals should take noise levels into account

Engines are usually produced as single- or multi- cylinder in line vertical engines, this configuration gained great interest. Although in practice three modes

are usually important, an engine has six degrees of freedom of vibration about orthogonal axes through its centre of gravity; these are linear vibrations along each axis and rotations about each axis. Vertical oscillations on the x- axis (unbalanced vertical forces), rotation about the y- axis (cyclic variations in torque), Rotation about the z- axis (unbalanced vertical forces in different transverse planes) are the important modes of an engine. The axes of an engine were shown in figure 3.5 (Plint, 2001).

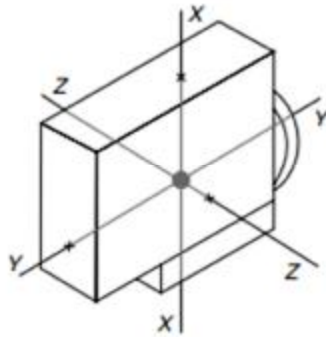


Figure 3.5. Axes of an internal combustion engine

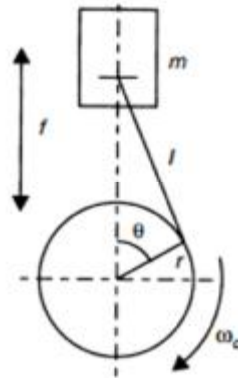


Figure 3.6. Connecting rod crank mechanism

In general, the rotating masses are carefully balanced but periodic forces due to the reciprocating masses cannot be avoided. A crank, connecting rod and piston assembly (figure 3.6) is subject to a periodic force in the line of action of the piston given in equation 3.3:

$$f = m_p \omega_c^2 r \cos \theta + \frac{m_p \omega_c^2 r \cos 2\theta}{n} \quad (3.3.)$$

Where;

$$n = l/r$$

m_p = sum of the mass of the piston and one third of the mass of the connection rod (the remaining two thirds is usually regarded as being concentrated at the crankpin centre)

The term of equation 3.3 represents the first order inertia force. It is equivalent to the component of centrifugal force on the line of action generated by a mass m_p concentrated at the crankpin and rotating at engine speed. The second term arises from the obliquity of the connecting rod and is equivalent to the component of force in the line of action generated by a mass $m/4n$ at the crankpin radius but rotating twice engine speed. Inertia forces of higher order (3x, 4x, etc. crankshaft speed) are also generated but may be ignored. It is possible to balance any desired proportion of the first order inertia force by balance weights on the crankshaft but these then give rise to an equivalent reciprocating force on the Z axis, which may be even more objectionable (Plint, 2001).

Inertia forces may be represented by vectors rotating at crankshaft speed and twice crankshaft speed. Figure 3.7 shows the first and second order vectors for engines having from one to six cylinders

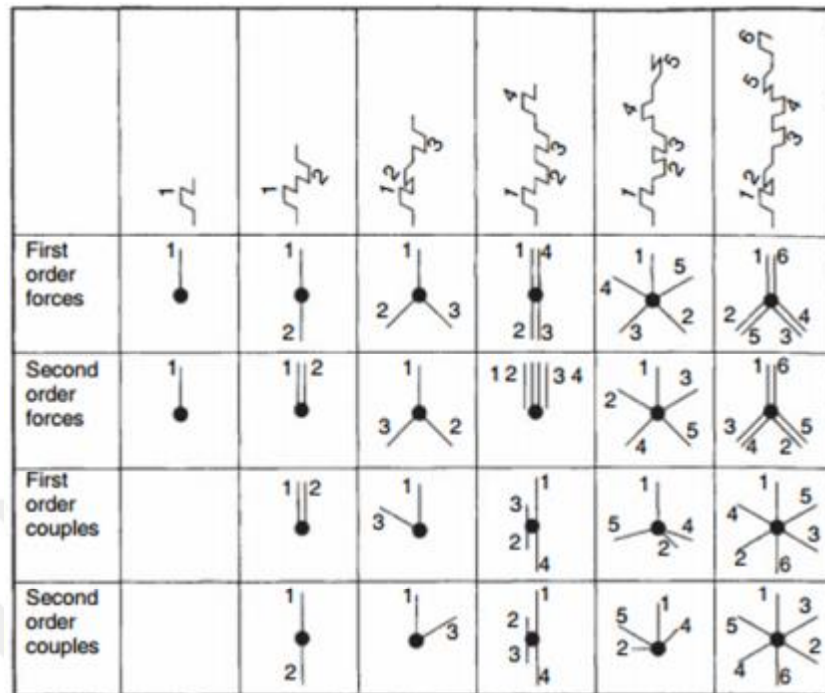


Figure 3.7. First and second order forces on engines

Following features should be taken into account in internal combustion engines:

- In a single cylinder engine both first and second order forces are unbalanced.
- For larger numbers of cylinders first order forces are unbalanced
- For two and four cylinder engines the second order forces are unbalanced. This is generally eliminated by counter-rotating weights driven at twice crankshaft speed.

The other consequence of reciprocating unbalance is the generation of rocking couples about the transverse or Z axis which are also shown in figure

- There are no couples in a single cylinder engine.
- In a two cylinder engine there is a first order couple.
- In a three cylinder engine there are first and second order couples.
- Four and six cylinder engines are fully balanced.

- In a five cylinder engine there is a small first order and a larger second order couple.
- Six cylinder engines are balanced in all modes (Plint, 2001).

Most instruments for measuring sound contain weighted networks which give a response to frequency approximates to the Fletcher-Munson curves. In other words their response to frequency is a reciprocal of the Fletcher-Munson relationship. For most applications the A-weighting curve gives satisfactory results and the corresponding SPL readings are given in dB(A). B- and C-weightings are sometimes used for high sound levels while a special D-weighting is used primarily for aircraft noise measurements.

The dB(A) value gives a general feel for the intensity and discomfort level of a noise but for analytical work the unweighted results should be used. The simplest type of sound level meter for diagnostic work is the octave band analyser. This instrument can provide flat or A-weighted indications of SPL for each octave in the standard range. For more detailed study of noise emissions an instrument it may for example be possible to pinpoint a particular pair of gears as a noise source.

For serious development work on engines, transmissions or vehicle bodies much more detailed analysis of noise emissions is provided by the Discrete Fourier Transform (DFT) or Fast Fourier Transform (FFT) digital spectrum analyser. The mathematics on which the operation of these instruments is based is somewhat complex but fortunately they may be used effectively without a detailed understanding of the theory involved. It is well known that any periodic function, such as the cyclic variation of torque in an internal combustion engine, may be resolved into a fundamental frequency and a series of harmonics. General noise from an engine or transmission does not repeat in this way and it is accordingly necessary to record a sample of the noise over a finite interval of time and to process this data to give a spectrum of SPL against frequency. The Fourier transform algorithm allows this to be done (Plint, 2001).

Fluid and mechanical impact are also important sources of high-frequency vibration and noise of an engine (Geng et al., 2003). Taking the often-encountered

cavitation noise for example, its spectrum has a wide-band distribution with a maximum frequency equal to:

$$f = \left(\frac{1}{2D_f}\right)\sqrt{P_f/\rho_f} \quad (\text{Hz}) \quad (3.4.)$$

Where;

f = frequency

D_f = diameter of the cavitation bubbles

P_f = breaking pressure of the cavitation bubbles

ρ_f = fluid density

The widely existing transient impacts caused by the inner-engine mechanical systems tend to be periodic at the operating rate of the engine when they cause high-frequency resonant responses of the impacting mechanical parts. Examples of this are the impacts caused by the inlet and outlet valves as well as the fatigue eroding of ball bearings, etc. The high-frequency resonant response possesses permanent frequency compositions and successively transforms itself as one part of the engine vibration. A maximum frequency component accord with the resonant frequency of the ball elements in the bearing was presented in equation 3.5:

$$f = \left(\frac{0,848}{D_b}\right)\sqrt{E_b/2\rho_b} \quad (\text{Hz}) \quad (3.5.)$$

Where;

f = frequency

D_b = diameter of the bearing's rolling elements

E_b = elasticity modulus of the bearing

ρ_b = material density of the ball bearing

The transient response caused by the inner-engine mechanical and fluid impacts possesses permanent frequency compositions. At the same time, the unstable

inner-cylinder working process and relative transmission relationship of the inner-engine mechanical systems irregularly modulate them. In consequence, the practically measured vibration signal on the engine casing expresses as a series of impulses modulated along the time history. Academically, this kind of time-varying impulsive signal can be classified as a specific type of point process, which is frequently encountered in the biomedical signal processing. Based upon the definition of point process, each impulse can be distinguished from the others by its impact intensity V_n (location and manner of the impacts) and occurrence time τ_n (relative transmission relationship of the inner-engine mechanical systems). Considering the irregularity of the engine combustion process as well as the randomness of the impact occurrence, the impact counting variable $N(r_j, t)$ is taken into account. Also considering the different type of impacts, respectively, caused by mechanical or fluid impact, the waveform of every impact arrived at time τ_n is introduced, denoted as (r_j, τ_n) (Geng et al., 2003). Then a global expression of the impact vibration response can be generally expressed as:

$$v(r_j, t) = \sum_{n=1}^{N(r_j, t)} V_n w(r_j, \tau_n) = \sum_{n=1}^{N(r_j, t)} V_n w(r_j, t) * \delta(t - \tau_n) \quad (3.6.)$$

Where;

$v(r_j, t)$ = impact-induced random vibration response

τ_n = impact happening time of the Poisson process, $n = 1, 2, \dots, N(r_j, t)$

t = time



4. MATERIAL AND METHOD

Experiments mentioned in this thesis were conducted in Petroleum Research and Automotive Engineering Laboratories of the Department of Automotive Engineering at Çukurova University and Mechanical Engineering Laboratories of the Adana Science and Technology University.

4.1. Preparation of Test fuels

In this study, sunflower, canola and corn oil were used as raw materials for biodiesel production since they are easily available in local oil companies in Turkey.

Biodiesel samples were produced via the transesterification reaction. In this reaction, methanol and sodium hydroxide were used as reactant and catalyst. The mixture was heated up to 60°C and kept at this temperature for 90 minutes by stirring. After the reaction period, the crude methyl ester was waited at separating funnel for 8 hours. And then, crude glycerine was separated from methyl ester. Then, the crude methyl ester was washed by warm water until the washed water became clear and then it dried at 110 °C for 1 hour. Finally washed and dried methyl ester was passed through a filter. Steps of biodiesel production were also briefly illustrated in Figure 4.1.

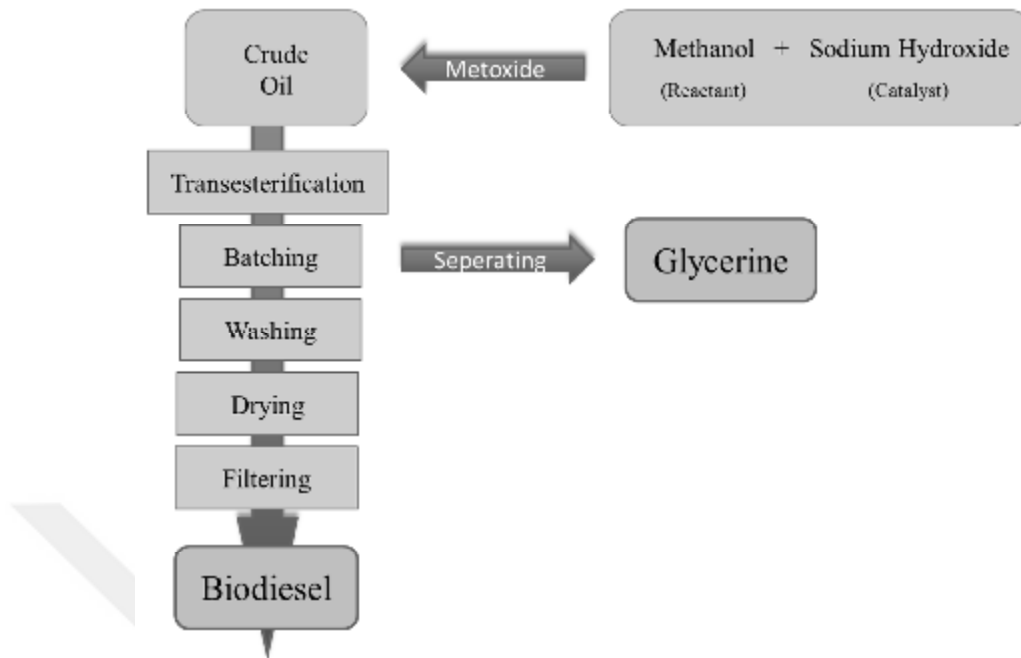


Figure 4.1. Biodiesel production steps

4.2. Determination of Fuel Properties

Fuel quality measurements of the test fuels were done according to TS EN 14214 standards. Kyoto Electronics DA-130 type densimeter (figure 4.2) was used for measure of fuel densities by using the resonant frequency method. The measurement interval of the device is 0 to 2 g/cm³ and 0 to 40 °C, ± 0.001 g/cm³ sensitivity, and a stability of 0.0001 g/cm³. The device is able to measure according to TS 6311 and ASTM D 4052-96 standards (Abdolvahitoğlu, 2009).



Figure 4.2. Kyoto Electronics DA-130 type densimeter

Zeltex ZX440 type device (figure 4.3) was used for determination of cetane numbers. It works under the close infrared spectrometer (NIR) principal to test the fuels very fast and cheap. The error of the device is 3%. (Tüccar, 2011).



Figure 4.3. Zeltex ZX440

The viscosities of the fuels were measured with Tanaka AKV-202 Automatic Kinematic Viscosity Measuring System (figure 4.4). Its standard test methods are ISO 3104, ASTM D445, IP71, etc. Once a specimen is set the series of timing, cleaning/drying of viscometer tube, and reporting processes are fully automated.



Figure 4.4. Tanaka AKV-202 Automatic Kinematic Viscosity Measuring System

IKA-Werke C2000 Bomb Calorimeter (figure 4.5) for gross heating value determination was used. Measurement of gross calorific values is according to ISO 1928, ASTM 240 D and its maximum measurement range value is 40.000 J.



Figure 4.5. IKA-Werke C2000 Bomb Calorimeter

Tanaka APM-7 Automated Pensky-Martens Closed Cup Flash Point Tester (figure 4.6) was used to determine flash point of the test fuels. It meets ISO 2719, ASTM D93, IP 34, etc. standards. Its measuring range is from ambient temperature to 370 °C (Abdulahitoğlu, 2009).

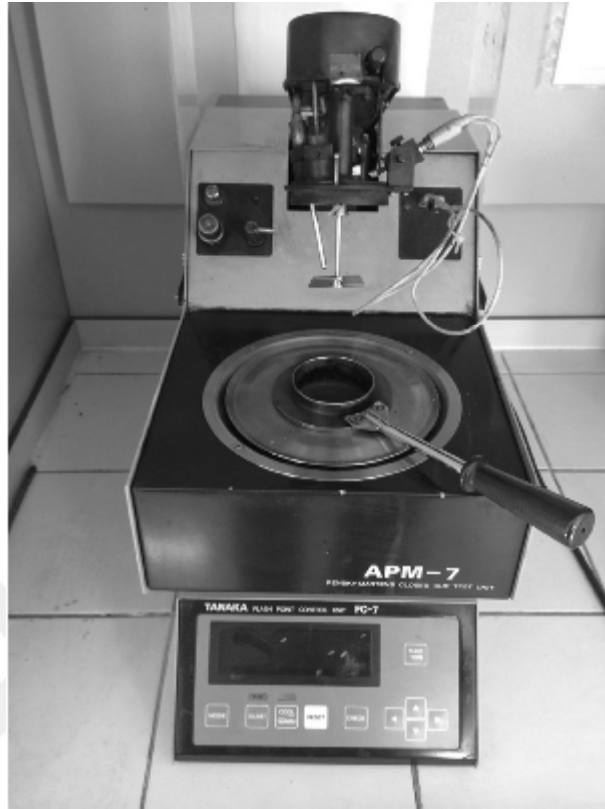


Figure 4.6. Tanaka APM-7 Automated Pensky-Martens Closed Cup Flash Point Tester

4.3. Engine Experiments

In this work, experiments were performed on two different four stroke, four cylinder, and direct injection diesel engine and on a single cylinder, four stroke, naturally aspirated, water cooled, variable compression multi fuel engine to validate test results. Before each experiment, the engines were warmed up to constant operating temperature and engine fuel line was cleaned before introduce with other fuel and waited until the engine became stable before the experimental data were gathered.

4.3.1. Experimental Engine 1

The experiments were firstly conducted on a Mitsubishi Canter 4D31, four stroke, four cylinder diesel engine and TT electric AMP 160-4B electrical

dynamometer at the engine speed of 1000 rpm, 1300 rpm, 1600 rpm, 1900 rpm, 2200 rpm, 2500 rpm and 2800 rpm when it was fuelled with low sulphur diesel (D100), 80% diesel, 20% sunflower biodiesel (SB20), 60% diesel, 40% sunflower biodiesel (SB40), 40% diesel, 60% sunflower biodiesel (SB60), 20% diesel, 80% sunflower biodiesel (SB80), 80% diesel, 20% canola biodiesel (CaB20), 60% diesel, 40% canola biodiesel (CaB40), 40% diesel, 60% canola biodiesel (CaB60), 20% diesel, 80% canola biodiesel (CaB80), 80% diesel, 20% corn biodiesel (CoB20), 60% diesel, 40% corn biodiesel (CoB40), 40% diesel, 60% corn biodiesel (CoB60), 20% diesel, 80% corn biodiesel (CoB80), by volume with pure sunflower (SB100), canola (CaB100), and corn (CoB100) biodiesels. Vibration data were gathered from engine support in three orthogonal axes of the engine (x- vertical axis; y- lateral axis, and z- longitudinal axis). Experimental layout is shown in figure 4.7 and its specifications were given in table 4.1.

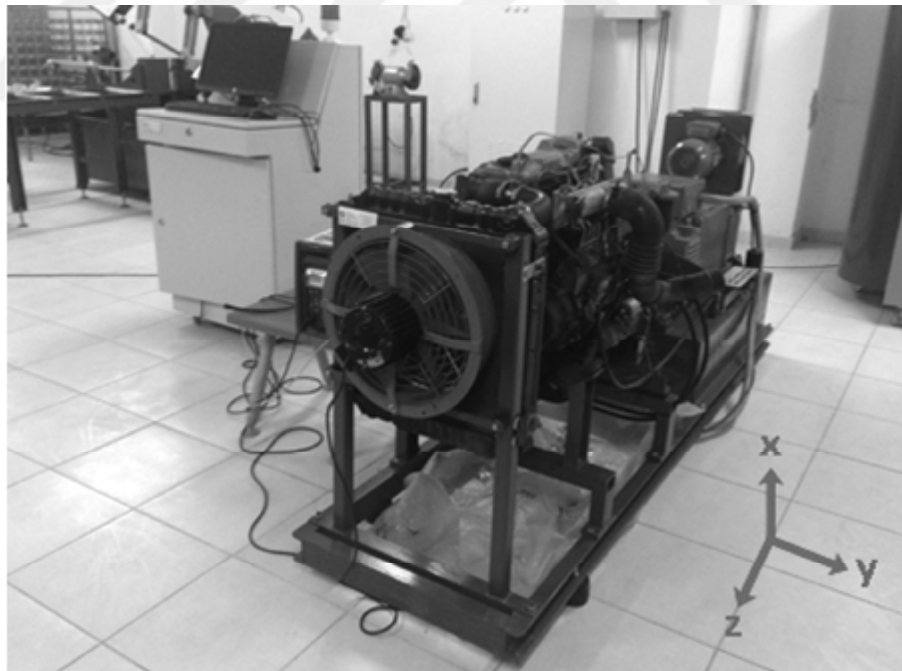


Figure 4.7. Layout of experimental setup

Table 4.1. Technical specifications of the test engine

Brand	Mitsubishi Canter
Model	4D31
Configuration	In line 4
Type	Direct injection diesel with glow plug
Displacement	3298cc
Bore	100
Stroke	105
Power	91 HP @ 3500rpm
Torque	223 Nm @ 2200rpm
Oil Cooler	Water cooled

4.3.2. Experimental Engine 2

Noise, vibration and emission experiments with low sulphur diesel, sunflower biodiesel, canola biodiesel, corn biodiesel and their blends were performed on a Mitsubishi Canter 4D34-2A, four stroke, four cylinder diesel engine. Experiments were conducted in a sound insulated room. Furthermore, periphery of dynamometer was covered by a wooden box with sound absorber panels.

H₂ and CNG were injected through intake air of the engine when it fuelled with diesel-biodiesel fuel blends. Experimental layout is shown in figure 4.8 and engine specifications were shown in table 4.2.

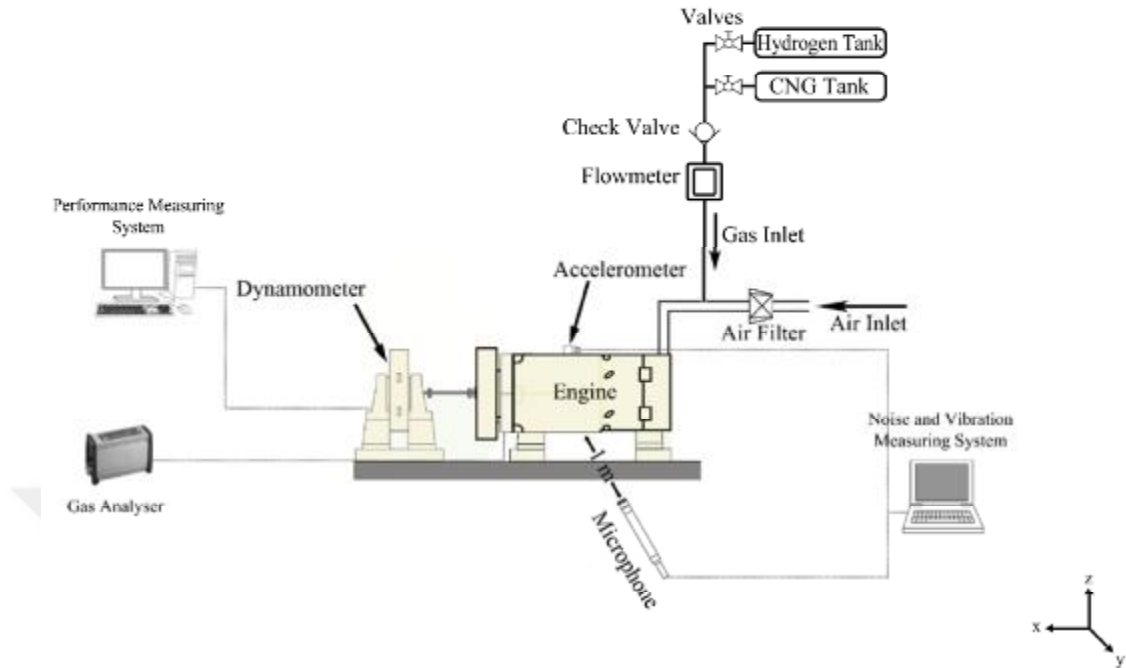


Figure 4.8. Experimental layout

Table 4.2. Technical specifications of the test engine.

Brand	Mitsubishi Canter
Model	4D34-2A
Configuration	In line 4
Firing order	1-3-4-2
Type	Direct injection diesel with glow plug
Displacement	3907 cc
Bore	104 mm
Stroke	115 mm
Power	89 kW @ 3200 rpm
Torque	295 Nm @ 1800 rpm
Oil cooler	Water cooled
Weight	325 kg

CNG was injected through intake manifold into intake air with different flow rates; 5 litre per minute (l/min) (NG5), 10 l/min (NG10), and 15 l/min (NG15), while the H_2 was added into the intake manifold with various flow rates of 3 l/min (H3),

and 6 l/min (H6). The gases were injected to the engine when fuelled with only D100, SB20, SB40, CaB20, and CaB40, CoB20, and CoB40 fuels since they fulfil the biodiesel standard of EN 14214. The rest of the blended fuels were not performed with gas additions in case of engine damage. Flow rate of the gases were adjusted by a control valve that placed before the flow meter.

Tests were conducted at 1200, 1500, 1800, 2100, and 2400 rpm engine speeds under no load condition.

4.3.3. Experimental Engine 3

Kirloskar Oil Engine-240 diesel engine was used for experiments in order to observe the effect of compression ratio and engine load on engine noise and vibration. The engine was fuelled with D100, SB20, SB40, SB60, SB80, SB100, CaB20, CaB40, CaB60, CaB80, CaB100, CoB20 CoB40, CoB60, CoB80, CoB100 biodiesels throughout the experiments. Engine specifications of this engine were given in table 4.3 and experimental layout was illustrated in figure 4.9.

Table 4.3. Technical specifications of the variable compression ratio (VCR) engine

Brand	Kirloskar Oil Engines
Model	240
Configuration	Single Cylinder
Type	Four Stroke, Water Cooled
Displacement	661 cc
Bore	87.5 mm
Stroke	110 mm
Maximum/Minimum Operating Speed	2000/1200 rpm
Power	3,5 Kw @ 1500 rpm
Compression Ratio (CR) range	12:1-18:1
Injection Variation	0-25 Deg BTDC
Peak Pressure	77.5 kg/cm ²
Air cleaner	Paper element type
Weight	160 kg
Combustion Principle	Compression Ignition
Lubricating System	Forced Feed System

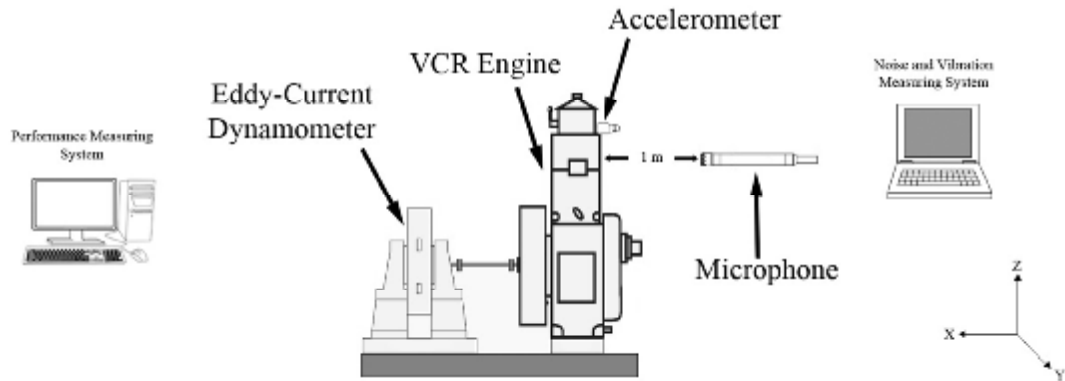


Figure 4.9. Schematic representation of test-rig

4.4. Measuring System

Acoustic and vibration data were recorded via Soundbook™ universal portable measuring system with SAMURAI v2.6 software from SINUS Messtechnik GmbH and the Toughbook™ CF-19 from Panasonic portable PC (figure 4.9). The software is capable to once or twice integrate a signal coming from accelerometer sensor in order to measure velocity and displacement. It is also capable to double integration of the time signal as filtering according to ISO 10816, ISO 7919 and ISO 2954 standards and the measurement range of the vibration meter is 2 Hz to 20 kHz. Sound level meter (SLM) of the software meets the Class 1 SLM according to IEC 60651, IEC 60804, DIN EN 61672-1:2003 standards allowing simultaneous measurements with the frequency weightings A, C, Z.

4.4.1. Accelerometer

Triaxial ICP® accelerometer sensor from PCB electronics model 356A33 was adhered on engine support and block with quick bonding gels to measure the vibration even in high frequency range. Data were collected in three orthogonal of the test engine. The accelerometer was illustrated in figure 4.10 and its properties are given in table 4.4.

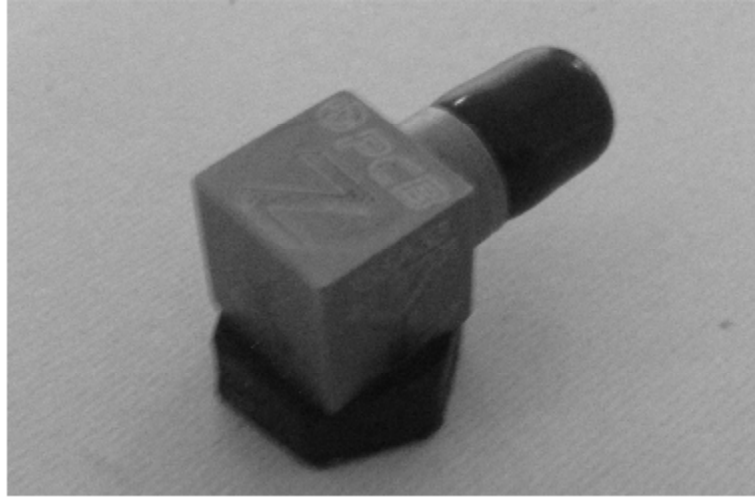


Figure 4.10. 356A33 model from PCB electronics accelerometer

Table 4.4. Specifications of accelerometer

Brand	PCB Electronics
Model	356A33
Sensitivity (± 10 %)	1.02 mV/(m/s ²
Measurement Range	± 4905 m/s ² pk
Frequency Range (± 5 %) (y or z axis)	2 to 10000 Hz
Frequency Range (± 5 %) (x axis)	2 to 7000 Hz
Resonant Frequency	≥ 55 kHz
Broadband Resolution (1 to 10000 Hz)	
Overload Limit (Shock)	± 98100 m/s ² pk
Temperature Range (Operating)	-54 to +121 °C
Sensing Element	Ceramic
Sensing Geometry	Shear
Housing Material	Titanium
Sealing	Hermetic
Electrical Connector	1/4-28 4-Pin

4.4.2. Microphone

Noise analysis of the engine was measured by using a GRAS 46AF 1/2" LEMO half-inch Free-field Standard Microphone Set (figure 4.11). It was optimized for all acoustic applications, where the location of the main sound source is known and the microphone can be pointed directly. The microphone was placed 1 meter away from the engine blocks in all test rigs. Specifications of the microphone were presented in table 4.5.



Figure 4.11. GRAS 46AF 1/2" LEMO Free-field Standard Microphone Set

Table 4.5. Specifications of microphone

Brand		GRAS
Model		46AF
Frequency range (± 1 dB)	Hz	5 to 10 k
Frequency range (± 2 dB)	Hz	3.15 to 20 k
Dynamic range lower limit with G.R.A.S. preamplifier	dB(A)	17
Dynamic range upper limit with G.R.A.S. preamplifier @ +28 V / ± 14 V power supply	dB	142
Dynamic range upper limit with G.R.A.S. preamplifier @ +120 V / ± 60 V power supply	dB	149
Set sensitivity @ 250 Hz (± 2 dB)	mV/Pa	50
Set sensitivity @ 250 Hz (± 2 dB)	dB re 1V/Pa	-26
Temperature range, operation	$^{\circ}\text{C}$	-30 to 70
Temperature range, storage	$^{\circ}\text{C}$	-40 to 85

4.4.3. Gas Analyzer

MRU Delta 1600-V gas analyzer is used to measure exhaust emissions. Emission data was collected by the help of a computer program. Measurement range and accuracy of the gas analyzer is given in table 4.6.

Table 4.6. Specifications of gas analyser

Brand		MRU GmbH
Model		Delta 1600-V
Electrochemical cell		
CO	Range	0 – 4000 ppm
	Accuracy	± 20 ppm or 5% reading below 4000 ppm
NO	Range	0 – 1000 ppm, overload up to 1000 ppm
	Accuracy	± 5 ppm or 5% reading below 1000 ppm, 10% reading above 1000 ppm
NO ₂	Range	0 – 200 ppm, overload up to 1000 ppm
	Accuracy	± 5 ppm or 5% reading below 200 ppm, 10% reading above 200 ppm
With NDIR Multi-gas bench		
CO ₂	Range	- 20 %
	accuracy	± 0,5 % or 5% reading

4.4.4. Calculations

Time and frequency domains were analysed in x (longitudinal), y (lateral) and z (vertical) axes. Since RMS (root mean square) value is the most relevant measure of vibration level (it gives an amplitude value by considering time history of the wave), the results were described as RMS value (figure 4.12).

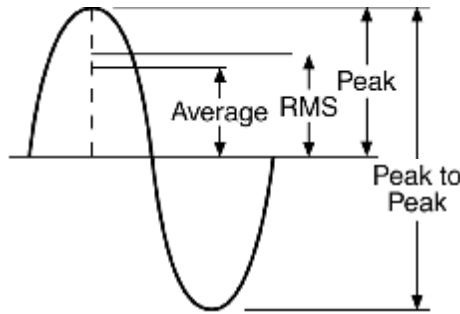


Figure 4.12. Representation of average, RMS, peak, and peak to peak on a waveform

Formula that was used to calculate RMS value was presented in equation 4.1. a_w (m/s²) represents the weighted acceleration and T represents measurement time.

$$a_w = \sqrt{\frac{1}{T} \int_0^T a_w^2(t) dt} \quad (\text{m/s}^2) \quad (4.1.)$$

Total vibration acceleration (a_{total}) is the value to show combined acceleration of vertical (a_x), lateral (a_y) and longitudinal (a_z). It was calculated by the formula given in equation 4.2.

$$a_{\text{total}} = \sqrt{a_x^2 + a_y^2 + a_z^2} \quad (\text{m/s}^2) \quad (4.2.)$$

The concept of sound intensity is the starting point of various quantitative aspects of noise measurement. It basically defines as;

$$I = \frac{\overline{p}^2}{\rho c} \quad (\text{W/m}^2) \quad (4.3.)$$

Where;

$\overline{p}^2$ = mean square value of the acoustic pressure

ρ = the density of air

c = The velocity of sound in air

Intensity is measured in a scale of decibels (dB) as shown in equation 4.4:

$$dB = 10 \log_{10} \left(\frac{I}{I_o} \right) = 20 \log_{10} \left(\frac{\bar{p}}{\bar{p}_o} \right) \quad (4.4.)$$

Where;

I_o = corresponds to the average lower threshold of audibility, taken by convention as $I_o = 10^{-12} \text{ W/m}^2$

From the definitions, it means that a doubling of the sound intensity causes 3 dB increases ($\log_{10} 2 = 0,301$). The value on the decibe scale is often referred to as the sound pressure level (SPL). In general sound is propagated spherically from its source and the inverse square law applies. Doubling the distance results in a reduction in SPL of about 6 dB ($\log_{10} 4 = 0,602$)

The human ear is sensitive to frequencies in the range from roughly 16 Hz to 20kHz, but the perceived level of a sound depend heavily on its frequency structure (Plint, 2001).

4.5. Linear and Non-Linear Regression Analysis

Before performing the analysis, correlation coefficients between all parameters were identified by using “corrcoef” command in MATLAB. Parameters which were selected as input in order to estimate outputs should be determined according to correlation coefficients between them. Therefore, all proper predictors which have higher correlation coefficients were selected to define each of predicted values. Since density, cetane number, kinematic viscosity, and gross heating value have strongly affected combustion characteristics which directly related to noise and vibration of a compression ignition engine, these parameters were selected as input for estimation.

One of the most widely used method to relate dependent variable(s) with independent variable(s) is regression analysis. It is a statistical process to find

functional relationship between variables. Regression analysis is mostly used for prediction.

In linear regression, the function is linear equation and dependent variable can be expressed as a function of independent variable(s) in form of (Bilgili and Şahin, 2010):

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_n X_n \quad (4.6.)$$

In non-linear regression, the function is non-linear equation and dependent variable can be expressed as a function of independent variable(s) in form of (Bilgili and Şahin, 2010):

$$Y = a_0 (X_1^{a_1}) (X_2^{a_2}) \dots (X_n^{a_n}) \quad (4.7.)$$

Where Y is dependent variable, β_0 to β_n and a_0 to a_n are equation parameters and X_1 to X_n are independent variables.



5. RESULT AND DISCUSSION

5.1. Fuel Properties

Mixtures of sunflower, canola, and corn methyl esters were used as biodiesel fuels and 100% low sulphur diesel fuel was used as reference fuel. Biodiesel and reference fuels were mixed in the volumetric ratio of 20%, 40%, 60%, and 80%. Mixtures of test fuels were prepared just before the experiments. Also, pure biodiesels were used as fuels. Quality measurements of the fuels were performed according to TS EN 14214 biodiesel standard and EN 590 diesel standard. Fuel properties were given in Table 5.1.

Table 5.1. Fuel Properties of the test fuels.

Test Fuels	Density (kg/m ³)	Cetane Number	Kinematic Viscosity at 40°C (mm ² /s)	Gross Heating Value (kJ/kg)	Flash point (°C)
D100	837	59,3	2,7	45857	74,5
SB20	844	56,5	3,1	44246	101,5
SB40	854	53,6	3,4	43430	106,5
SB60	869	51,1	3,7	42998	
SB80	876	49,0	4,1	41874	
SB100	886	44,5	4,5	39149	>140
CaB20	846	56,9	3,2	43413	76,7
CaB40	857	54	3,5	42986	83,9
CaB60	861	51,8	3,8	41568	
CaB80	869	50	4,0	39974	
CaB100	883	46	4,7	38363	120,5
CoB20	847	55,4	3	42266	85,5
CoB40	856	52,1	3,2	41881	91,5
CoB60	862	48,9	3,5	39368	
CoB80	870	45	3,8	38158	
CoB100	887	42,2	4,2	37476	>140
EN590	820–845	Min 51	2,0–4,5	-	Min 55
ASTM D 6751	-	Min 47	1,9–6,0	-	Min 93
EN 14214	860 - 900	Min 51	3,5 – 5,0	-	Min 120

The densities of biodiesels were higher than that of low sulphur diesel fuel. Therefore densities of blends were between pure low sulphur diesel and pure biodiesels. The highest density was measure with CoB100 fuel.

Cetane number is an important parameter to the evaluation of the self-ignitability of fuel. Cetane number of pure sunflower, canola and corn biodiesels doesn't meet the standard of EN 14214 biodiesel standard. Blend of sunflower and canola biodiesels are able to meet the standard up to 60%, whereas corn biodiesel is able to meet it up to 40% blend.

One of the most important drawbacks of using biodiesel fuel into an unmodified diesel engine is its high viscosity. Higher viscosity; which results in less accurate operation of the fuel injectors, poorer atomization of the fuel spray, increase in the sauter mean diameter of the fuel droplets and of the breakup time of the fuel droplets, viscosity depends upon the degree of unsaturation and with the fatty acid chain length (Kumar and Rehman, 2016). Fuel property experiments revealed that, sunflower, canola and corn biodiesels have higher viscosity value than low sulphur diesel fuel.

Gross heating value on account of oxygen proportion in the biodiesel, which necessitates the greater mass of biodiesel to be injected to get the same engine power (Kumar and Rehman, 2016). It decreased by increasing biodiesel proportion into the mixture.

The flash point is the temperature at which the fuel will give off enough vapor to produce a flammable mixture. This is important information for the safe transportation, storage of the fuel (Tüccar, 2011). It found out that all pure biodiesels meet the standard of EN 14214.

5.2. Engine experiments

5.2.1. Experimental Engine 1

In this test rig Mitsubishi Canter 4D31 four stroke, four cylinder diesel engine was fuelled with D100, SB20, SB40, SB60, SB80, SB100, CaB20, CaB40, CaB60,

CaB80, CaB100, CoB20, CoB40, CoB60, CoB80, and CoB100 in order to observe their effect on engine vibration. The engine was run at 1000 rpm, 1300 rpm, 1600 rpm, 1900 rpm, 2200 rpm, 2500 rpm, and 2800 rpm engine speeds.

Figure 5.1-7 represent the time and frequency domain signal spectrums of the test engine when it was fuelled with D100 at different operating speeds (1000 rpm, 1300 rpm, 1600 rpm, 1900 rpm, 2200 rpm, 2500 rpm, and 2800 rpm, respectively).

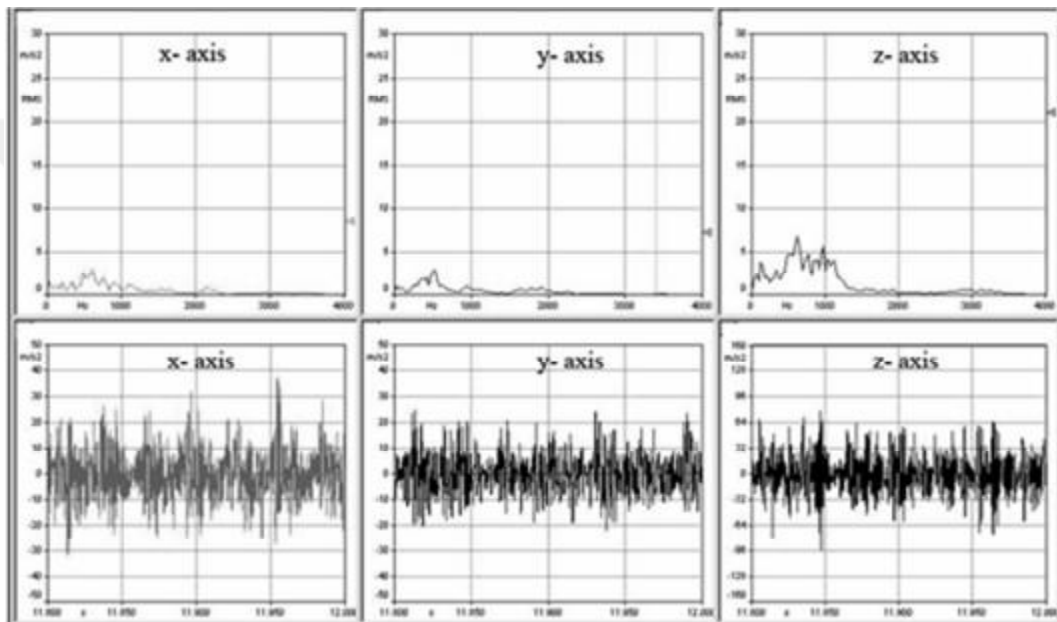


Figure 5.1. Time and frequency analysis of the engine that fuelled with D100 at 1000 rpm

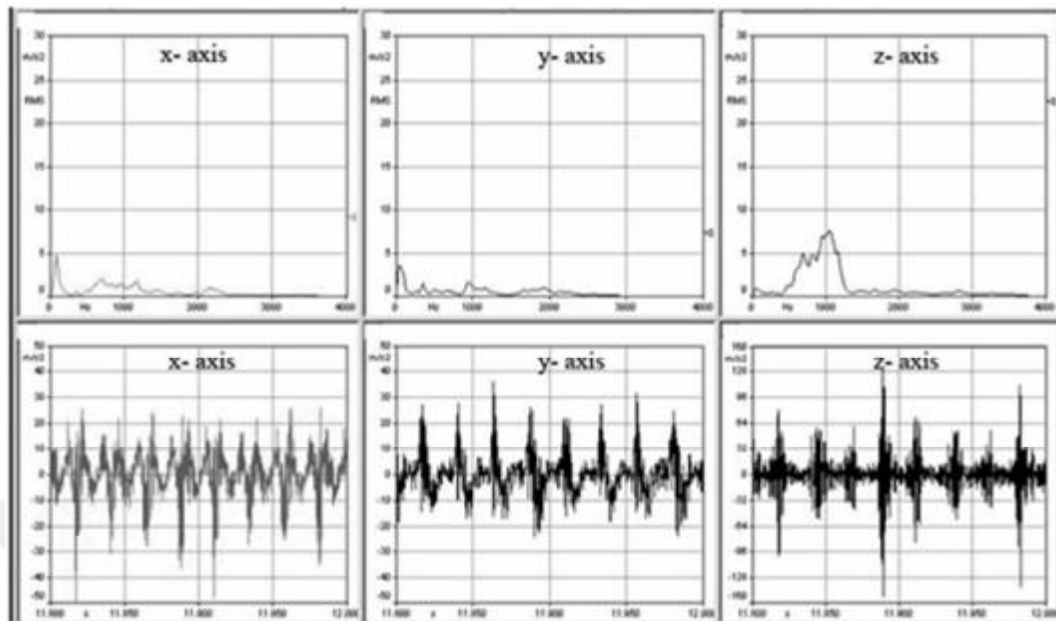


Figure 5.2. Time and frequency analysis of the engine that fuelled with D100 at 1300 rpm

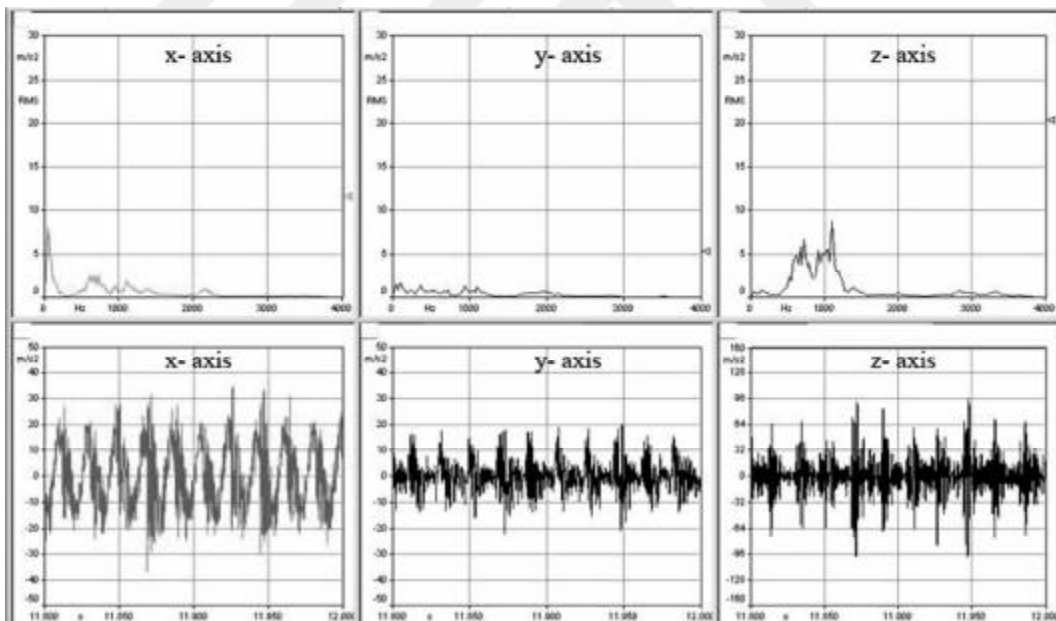


Figure 5.3. Time and frequency analysis of the engine that fuelled with D100 at 1600 rpm

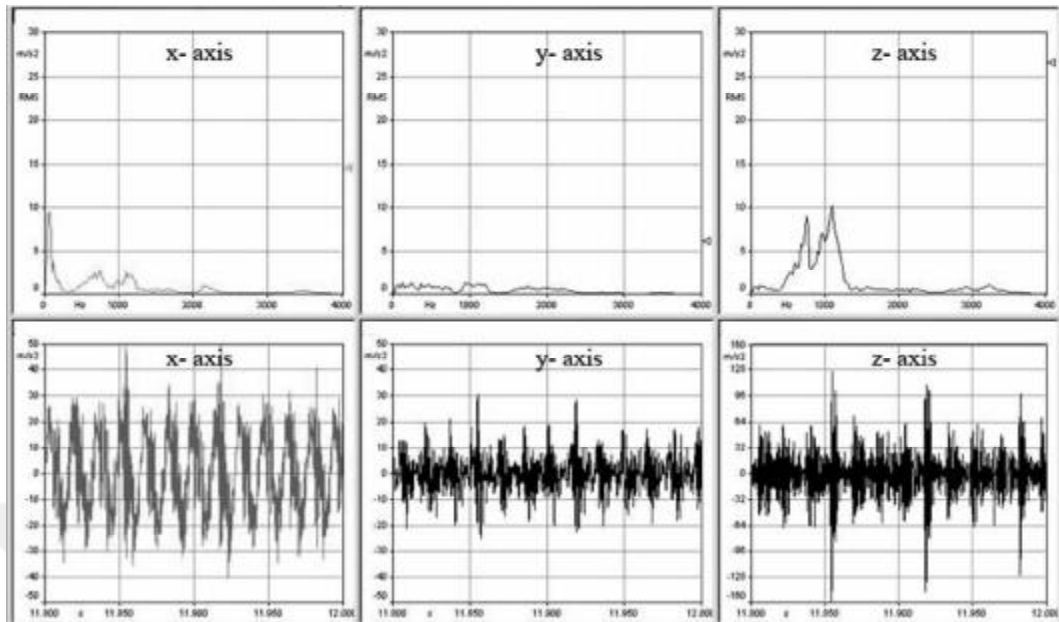


Figure 5.4. Time and frequency analysis of the engine that fuelled with D100 at 1900 rpm

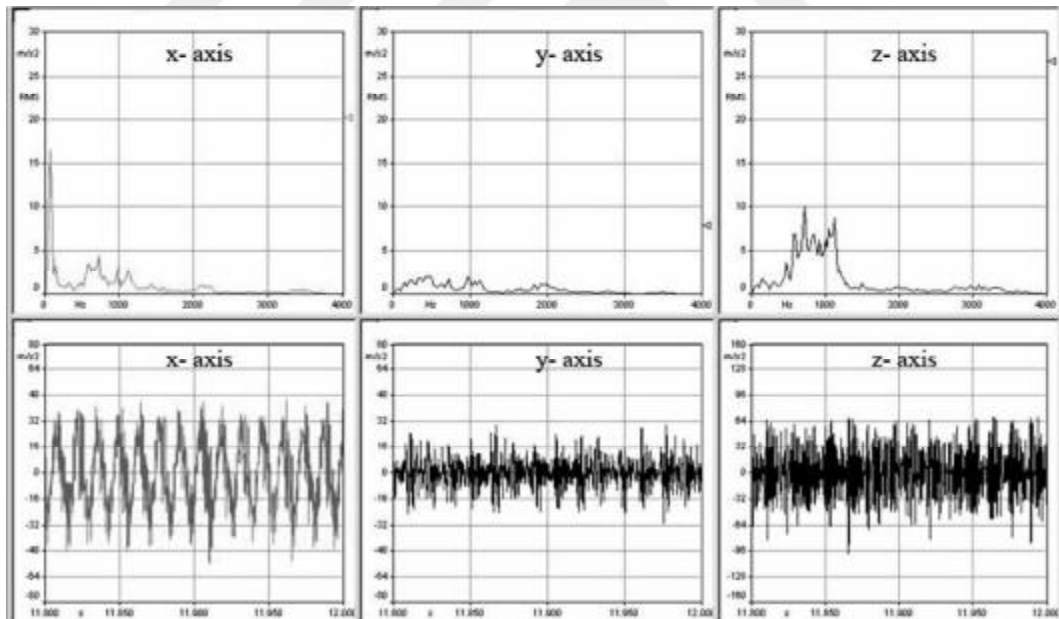


Figure 5.5. Time and frequency analysis of the engine that fuelled with D100 at 2200 rpm

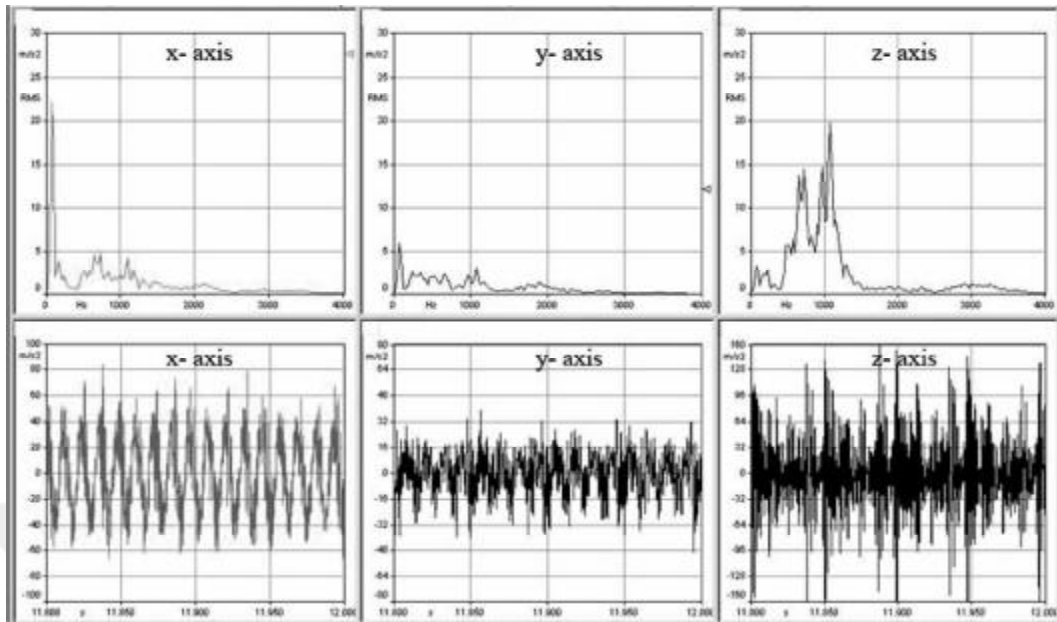


Figure 5.6. Time and frequency analysis of the engine that fuelled with D100 at 2500 rpm

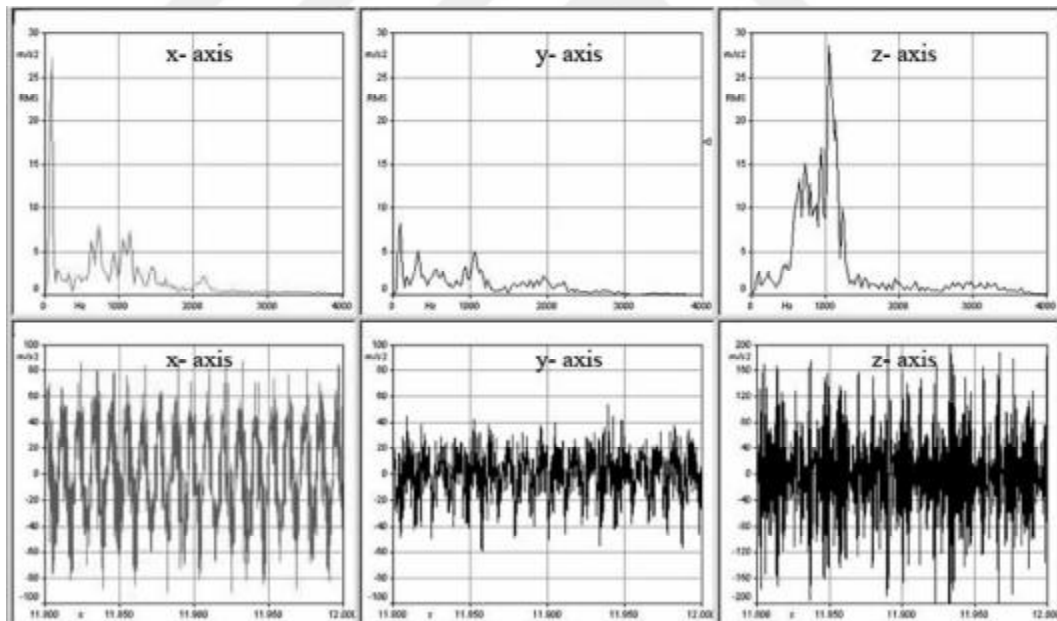


Figure 5.7. Time and frequency analysis of the engine that fuelled with D100 at 2800 rpm

Theoretically, at 1000 rpm, 1300 rpm, 1600 rpm, 1900 rpm, 2200 rpm, 2500 rpm, and 2800 rpm engine speeds, ignition frequency of four cylinder four stroke diesel engine is 33,33 Hz, 43,33 Hz, 53,33 Hz, 63,33 Hz, 73,33 Hz, 83,33 Hz, and 93,33 Hz, respectively. From above figures, it can be seen that the dominant

frequency was the piston stroke frequency of the engine occurred at x- (vertical) axis due to the upward and downward movement of the pistons. Fluid impact or mechanical impact such as eroding of ball bearing may have caused vibration at high frequencies. Also, the pistons, with high speed motion and complicated kinematic characteristics, are particularly vulnerable to the harsh engine operating conditions. Even so, apart from possible external shock loads or contaminated lubricant, metal to metal contact between the piston and the inner wall is usually limited except during startup and shutdown for normal clearance, but this can eventually lead to excessive wear and oversized clearances. With oversize clearance, the impact forces between the piston and cylinder inner wall increase, which greatly accelerates the wear (Chen et al., in press). Thus, these reasons may lead to the highest a_{total} values of all frequencies occurred in z- (longitudinal) axis. According to fuel type, at different engine speeds, vibration acceleration significantly changed along x- and z- axes whereas slight differences were observed at y- (lateral) axis due to vibration at x-axis depend on downward-upward piston movement increase with engine speed and the conversion of linear motion to rotational motion, a component of vertical force is directly transferred to the z- axes (Gravalos et al., 2013). All test results were given in following tables (table 5.2, 5.3, 5.4, 5.5, 5.6, 5.7, and 5.8).

Table 5.2. a_{rms} values of three orthogonal axis at 1000 rpm

	1000 RPM								
	Sunflower Biodiesel			Canola Biodiesel			Corn Biodiesel		
	x	y	z	x	y	z	x	y	z
D	8,11	6,85	22,17	8,11	6,85	22,17	8,11	6,85	22,17
B20	7,84	4,94	20,03	8,55	7,48	21,59	8,43	6,50	21,59
B40	7,31	4,76	18,43	7,97	6,69	19,04	7,94	6,02	19,04
B60	6,98	4,28	17,32	7,63	6,72	18,99	7,60	5,80	18,99
B80	6,01	3,96	14,49	7,74	7,26	19,64	7,17	5,90	19,64
B100	6,92	4,25	16,29	7,64	7,07	19,67	7,57	5,95	19,67

Table 5.3. a_{rms} values of three orthogonal axis at 1300 rpm

	1300 RPM								
	Sunflower Biodiesel			Canola Biodiesel			Corn Biodiesel		
	<i>x</i>	<i>y</i>	<i>z</i>	<i>x</i>	<i>y</i>	<i>z</i>	<i>x</i>	<i>y</i>	<i>z</i>
D	8,22	6,51	20,38	8,22	6,51	20,38	8,22	6,51	20,38
B20	6,79	4,89	11,44	7,58	6,75	16,43	7,48	6,11	14,43
B40	6,80	4,36	10,54	6,92	5,80	10,39	7,16	5,38	10,76
B60	6,77	4,32	10,33	7,00	5,73	9,37	7,18	5,32	10,14
B80	6,87	4,27	10,47	6,83	5,82	10,12	7,14	5,34	10,59
B100	6,90	4,38	10,35	7,13	5,82	9,48	7,30	5,39	10,21

Table 5.4. a_{rms} values of three orthogonal axis at 1600 rpm

	1600 RPM								
	Sunflower Biodiesel			Canola Biodiesel			Corn Biodiesel		
	<i>x</i>	<i>y</i>	<i>z</i>	<i>x</i>	<i>y</i>	<i>z</i>	<i>x</i>	<i>y</i>	<i>z</i>
D	11,62	5,05	20,63	11,62	5,05	20,63	11,62	5,05	20,63
B20	10,44	4,06	13,91	10,79	5,94	17,47	10,91	5,29	15,98
B40	10,31	3,70	12,45	9,97	4,85	11,79	10,43	4,57	12,42
B60	10,32	3,64	11,97	9,69	4,52	10,79	10,30	4,37	11,67
B80	10,41	3,66	12,87	10,11	4,56	12,67	10,56	4,40	13,07
B100	10,26	3,81	12,16	9,82	4,51	10,90	10,33	4,45	11,82

Table 5.5. a_{rms} values of three orthogonal axis at 1900 rpm

	1900 RPM								
	Sunflower Biodiesel			Canola Biodiesel			Corn Biodiesel		
	<i>x</i>	<i>y</i>	<i>z</i>	<i>x</i>	<i>y</i>	<i>z</i>	<i>x</i>	<i>y</i>	<i>z</i>
D	14,34	5,28	24,39	14,34	5,28	24,39	14,34	5,28	24,39
B20	13,61	4,29	16,71	13,81	6,24	20,63	14,00	5,56	18,96
B40	13,64	4,02	15,65	13,38	5,67	15,61	13,80	5,14	15,92
B60	13,65	3,99	15,75	13,18	5,55	14,41	13,71	4,98	15,37
B80	13,56	4,11	15,27	13,38	5,82	17,16	13,76	5,26	16,51
B100	13,60	4,12	14,21	13,40	5,76	15,29	13,79	5,23	15,04

Table 5.6. a_{rms} values of three orthogonal axis at 2200 rpm

	2200 RPM								
	Sunflower Biodiesel			Canola Biodiesel			Corn Biodiesel		
	<i>x</i>	<i>y</i>	<i>z</i>	<i>x</i>	<i>y</i>	<i>z</i>	<i>x</i>	<i>y</i>	<i>z</i>
D	20,11	6,81	26,38	20,11	6,81	26,38	20,11	6,81	26,38
B20	19,44	6,04	22,52	18,93	8,12	22,90	19,48	8,37	23,61
B40	19,97	5,83	21,49	18,69	7,89	19,39	19,63	7,15	20,73
B60	20,26	6,01	21,94	18,23	7,80	18,13	19,54	7,20	20,33
B80	20,45	5,98	22,04	18,84	8,17	19,53	19,94	7,37	21,08
B100	20,45	5,97	22,28	18,81	8,16	18,50	19,92	7,36	20,69

Table 5.7. a_{rms} values of three orthogonal axis at 2500 rpm

	2500 RPM								
	Sunflower Biodiesel			Canola Biodiesel			Corn Biodiesel		
	x	y	z	x	y	z	x	y	z
D	27,24	11,24	41,76	27,24	11,24	41,76	27,24	11,24	41,76
B20	27,28	10,70	36,78	26,48	13,22	38,71	27,17	12,25	38,04
B40	27,03	10,56	34,21	28,45	13,26	30,61	28,04	12,20	32,70
B60	26,87	10,74	34,84	28,71	12,86	29,26	28,08	12,09	32,34
B80	27,27	11,05	34,78	28,63	13,05	32,21	28,24	12,34	33,79
B100	27,01	11,01	34,73	28,46	12,51	31,01	28,03	12,05	33,16

Table 5.8. a_{rms} values of three orthogonal axis at 2800 rpm

	2800 RPM								
	Sunflower Biodiesel			Canola Biodiesel			Corn Biodiesel		
	x	y	z	x	y	z	x	y	z
D	34,52	14,87	58,63	34,52	14,87	58,63	34,52	14,87	58,63
B20	34,13	13,96	52,31	32,72	17,06	47,52	33,72	15,80	50,21
B40	34,41	13,32	48,09	34,23	14,28	41,82	34,61	14,10	45,25
B60	34,35	13,12	48,65	34,00	13,48	40,51	34,47	13,60	44,87
B80	34,47	12,92	49,40	34,40	14,35	45,50	34,73	13,93	47,74
B100	34,54	12,74	47,56	34,61	13,89	44,55	34,87	13,61	46,35

a_{total} value with different fuels were presented in Figure 5.8-10. According to these results; engine speed was significantly affected the engine vibration severity. Up to 60% canola and sunflower biodiesel addition, total a_{rms} values were decreased and the least vibration acceleration mostly observed with this blend ratio. For the blend of 80%, the total a_{rms} values started to increase. However, pure biodiesel caused slight reduction compared to 80% blends. This trend was observed at all engine speeds for most of the test fuel. In addition, it should be pointed out that the descents of total a_{rms} values were more significant until 40% biodiesel proportion. Canola biodiesel blends improved vibration amplitude more than sunflower biodiesel blends, whereas the highest a_{total} value was measured with corn biodiesel blends. At low engine speed, 1000 rpm, the values shows uncertainty compared to other engine speeds. This may due to combustion knock results from the spontaneous ignition of a portion of the end gas mixture in the combustion chamber ahead of the propagating flame. When this abnormal combustion occurs, there is a rapid release of chemical energy in the remaining unburned mixture, causing high local pressures and

generating propagating pressure waves with amplitude of several bars across the combustion chamber and these pressure waves are transmitted through the engine structure. The large amplitude pressure waves of the hot combusted gases in the cylinder are the primary reason for increment of engine vibration (Szwaja and Grab-Rogalinski, 2009).

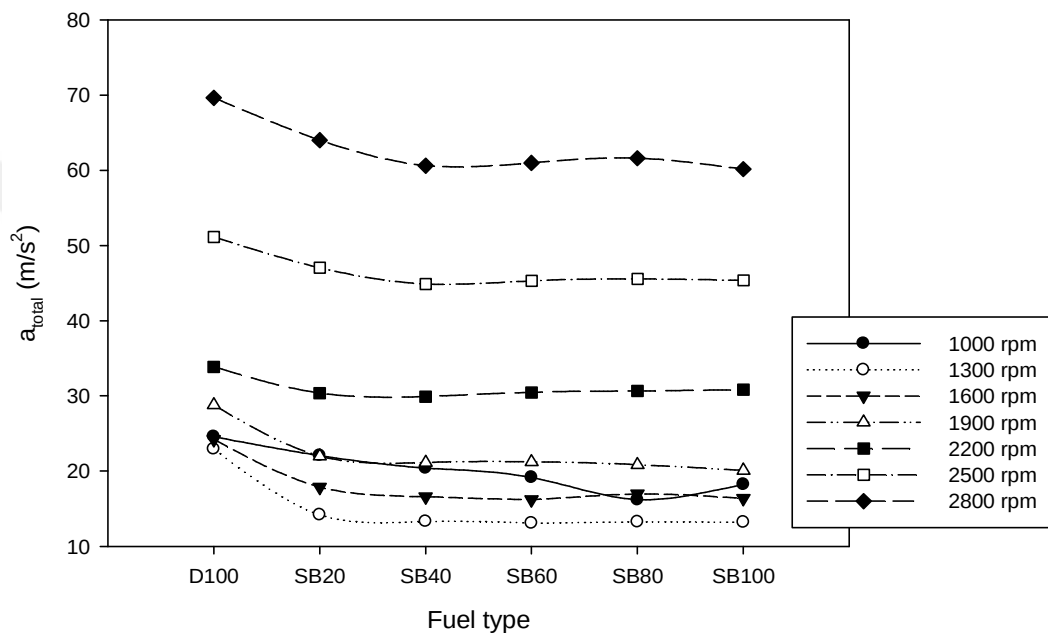


Figure 5.8. a_{total} values when Mitsubishi Canter 4D31 engine fuelled with sunflower biodiesel and its blends with low sulphur diesel engine

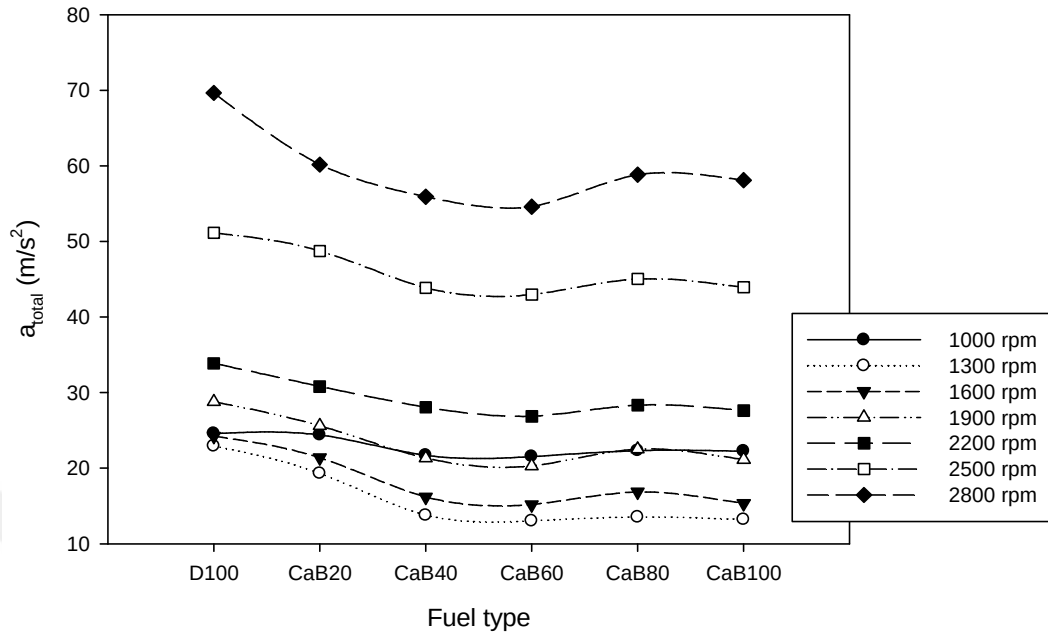


Figure 5.9. a_{total} values when Mitsubishi Canter 4D31 engine fuelled with canola biodiesel and its blends with low sulphur diesel engine

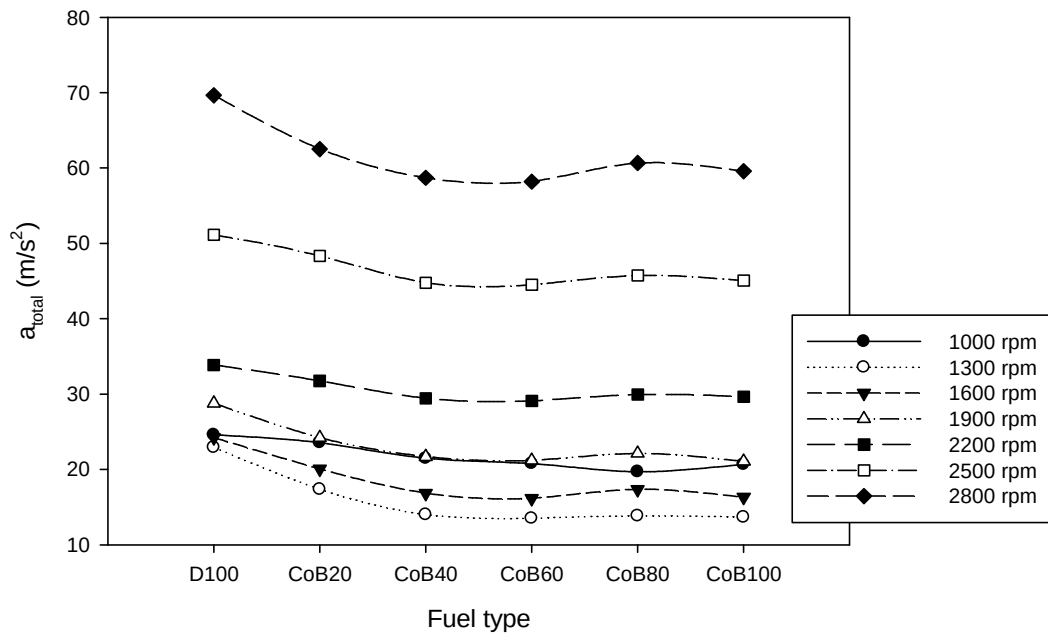


Figure 5.10. a_{total} values when Mitsubishi Canter 4D31 engine fuelled with corn biodiesel and its blends with low sulphur diesel engine

5.2.2. Experimental Engine 2

In this test rig the Mitsubishi Canter 4D34-2A diesel engine was fuelled with D100, SB20, SB40, SB60, SB80, SB100, CaB20, CaB40, CaB60, CaB80, CaB100, CoB20, CoB40, CoB60, CoB80, CoB100. Also NG5, NGG10, NG15 and H3, H6 gases were added through intake manifold of the engine.

5.2.2.1. Usage of Biodiesel Blends

In this section, vibration, noise, and exhaust emission characteristics of the engine when it was fuelled with biodiesel blends has been evaluated.

5.2.2.1.(1). Vibration

For each experiment, vibration data gathered from the engine block with 51,2 kHz sampling frequency for 12 seconds.

Vibration acceleration spectrum characteristics of the engine at different operating speed were illustrated in following figures (5.11-18). First columns of the figures belong to data of x- axis (longitudinal), second columns represent y- axis (lateral) and the last columns represent z- axis (vertical).

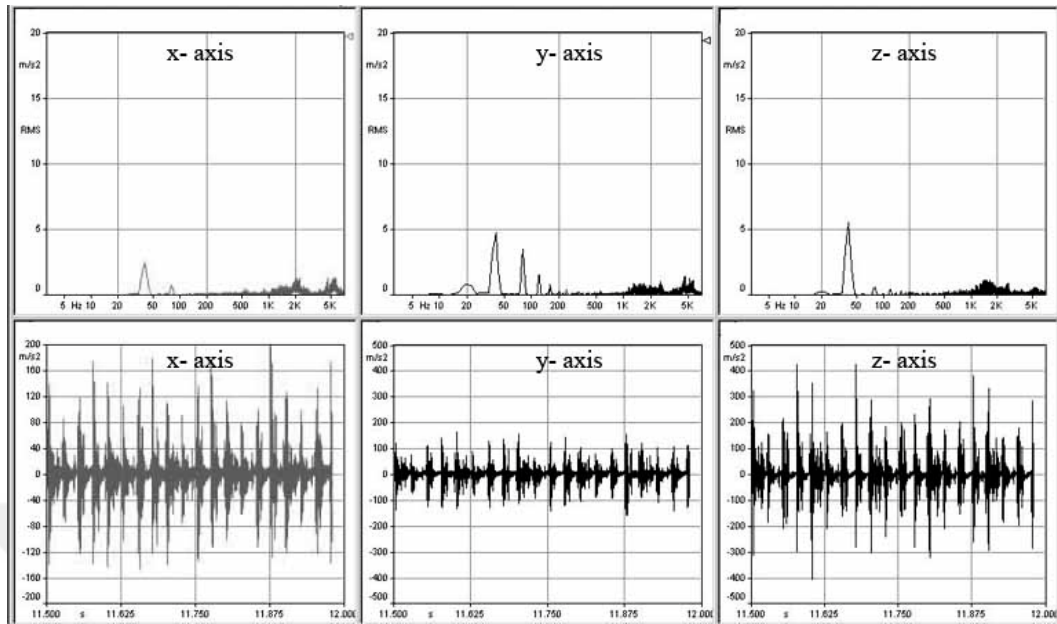


Figure 5.11. Time and frequency domain signal of the engine that fuelled with D100 at 1200 rpm

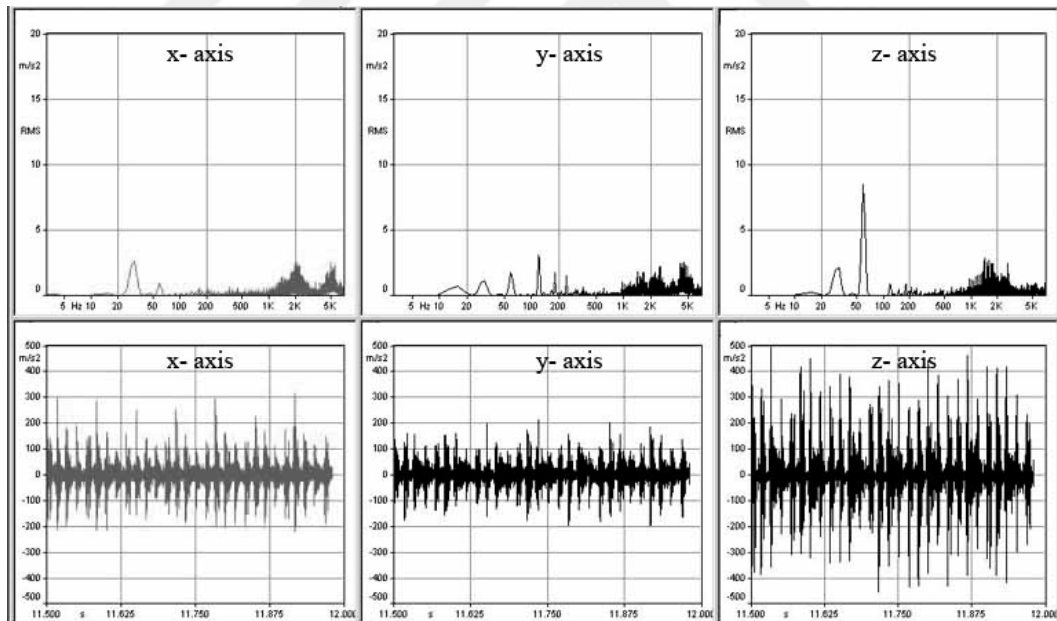


Figure 5.12. Time and frequency domain signal of the engine that fuelled with D100 at 1500 rpm

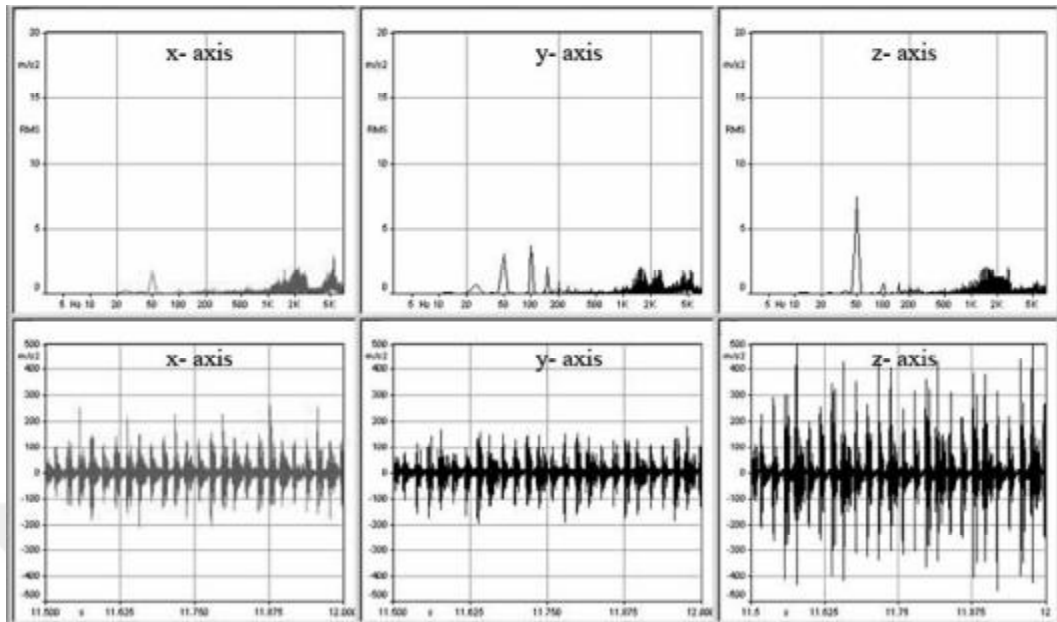


Figure 5.13. Time and frequency domain signal of the engine that fuelled with D100 at 1800 rpm

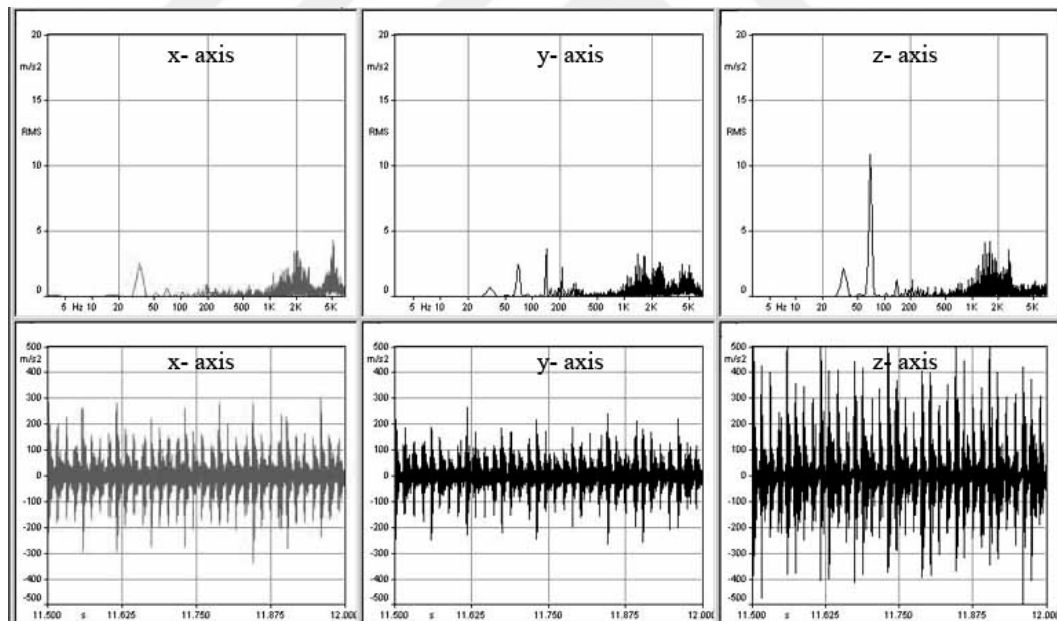


Figure 5.14. Time and frequency domain signal of the engine that fuelled with D100 at 2100 rpm

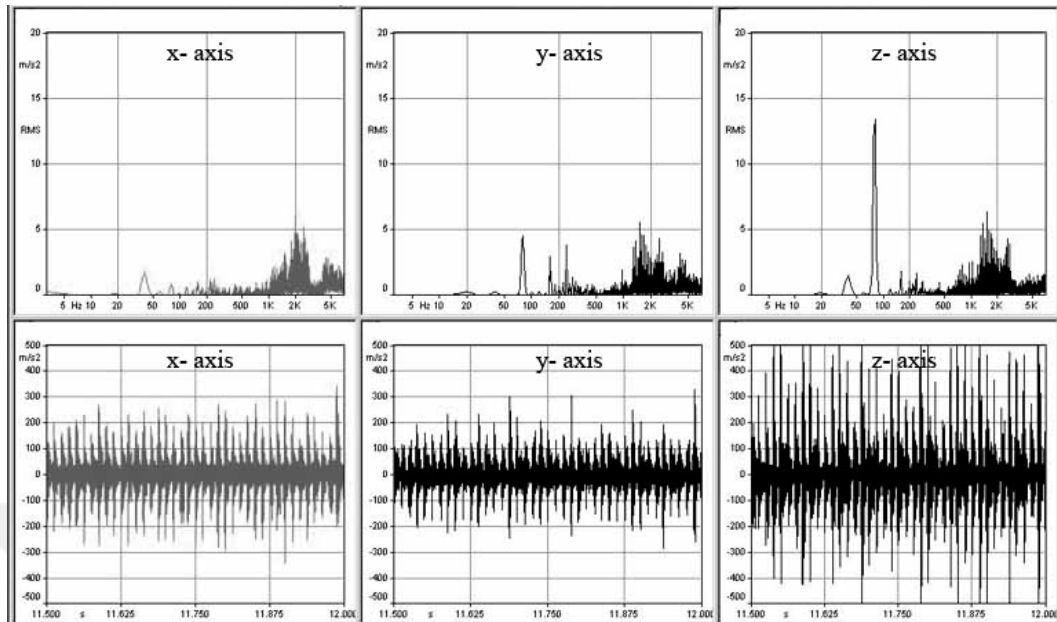


Figure 5.15. Time and frequency domain signal of the engine that fuelled with D100 at 2400 rpm

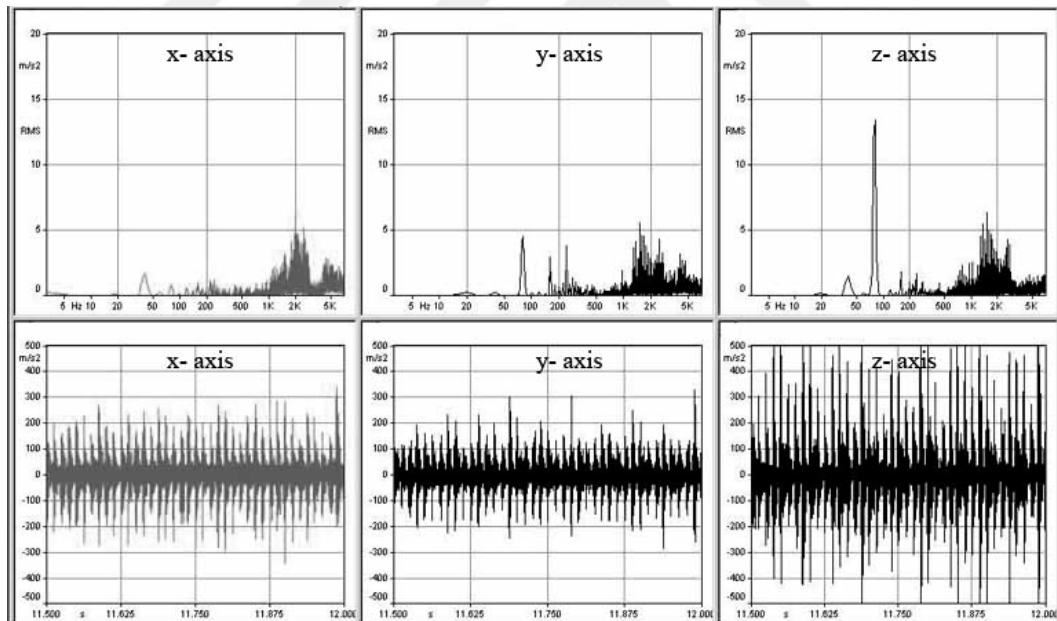


Figure 5.16. Time and frequency domain signal of the engine that fuelled with SB20 at 1500 rpm

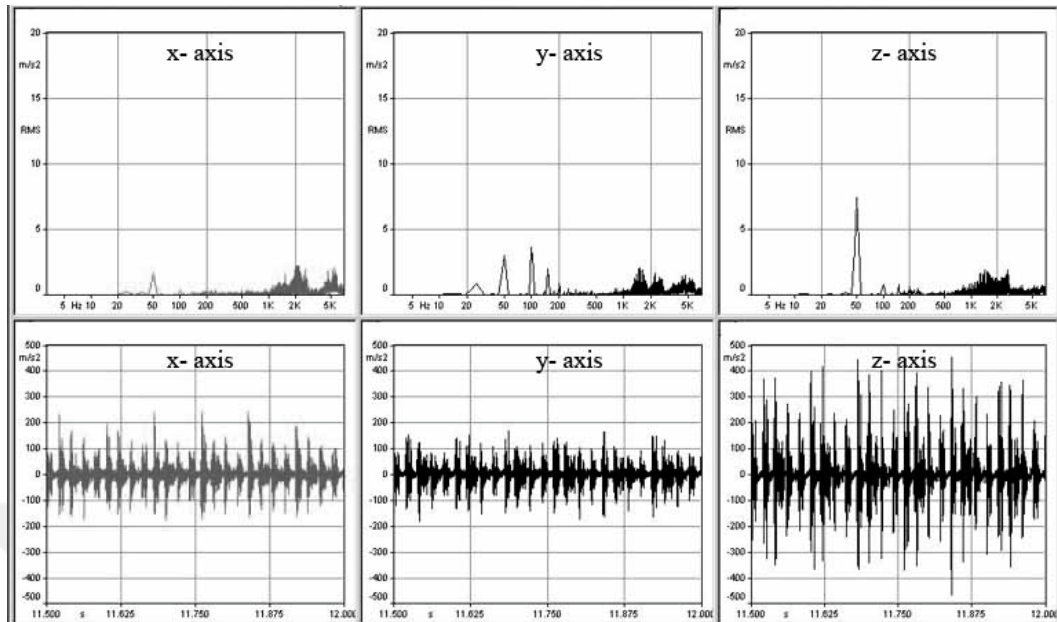


Figure 5.17. Time and frequency domain signal of the engine that fuelled with CaB20 at 1500 rpm

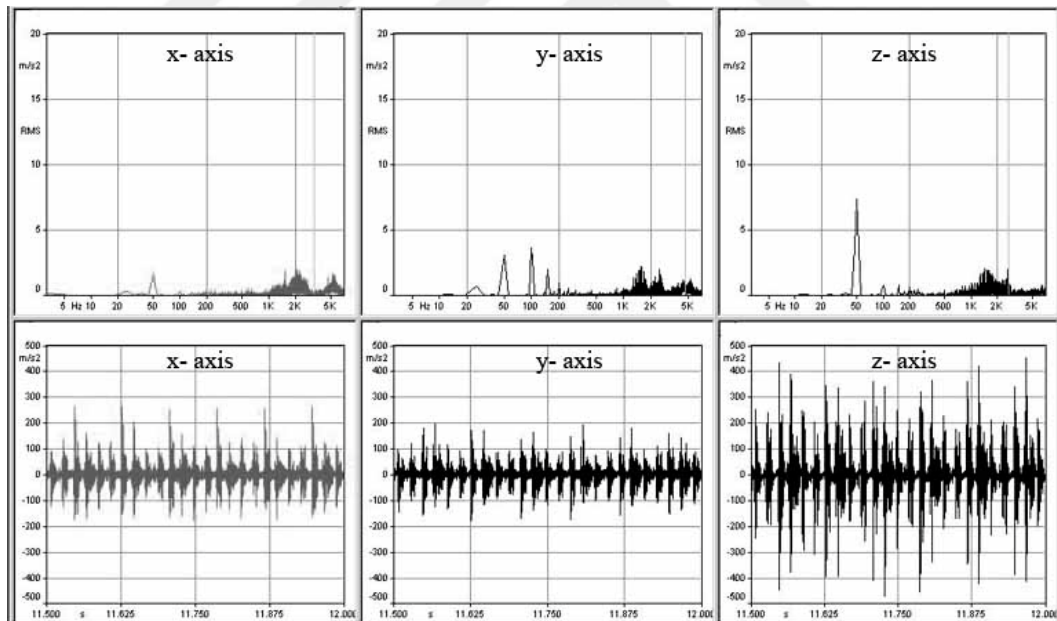


Figure 5.18. Time and frequency domain signal of the engine that fuelled with CoB20 at 1500 rpm

It is clear that the dominant frequency is the twice of engine speed as expected due to the upward and downward piston movement. Spectrum of the test engine may also characterize by a wide resonance zone and overlapped on worn auxiliary equipment which has different kinds of clearances (Dabrowski and

Komorska, 2012). One of the most important inputs during the work of the piston-crank mechanism are the impacts of the piston by the change of its work direction. Clearance between the piston and the cylinder wall which is caused by the exploitation consumption of the engine is significantly affect the value of input. Burning pressure function and the rotational speed of the engine function is the main value of the power. The received signal is strongly interfered by various vibration sources and that is why there is a necessity to use advanced methods of signal selection. Due to the impulsive character of the inputs, the spectral diagnostic bands are in the area of high frequencies. That is why there is a need to use the acceleration sensors with high transfer range and their proper fastening on the body or the piston of the engine (Czech, 2010).

In an internal combustion engine single events occur in a cycle sequence, and their repetition in each next cycle is a symptom of the working engine. Elementary events occurring in kinematic pairs occur also in an order. That is why, according to the place of impact impulse in respect of reference signal one can define an engine kinematic pair which created the impulse.

a_{total} values of the engine block were illustrated in following figures 5.19, 5.20, and 5.21, SB, CaB, and CoB blends, respectively.

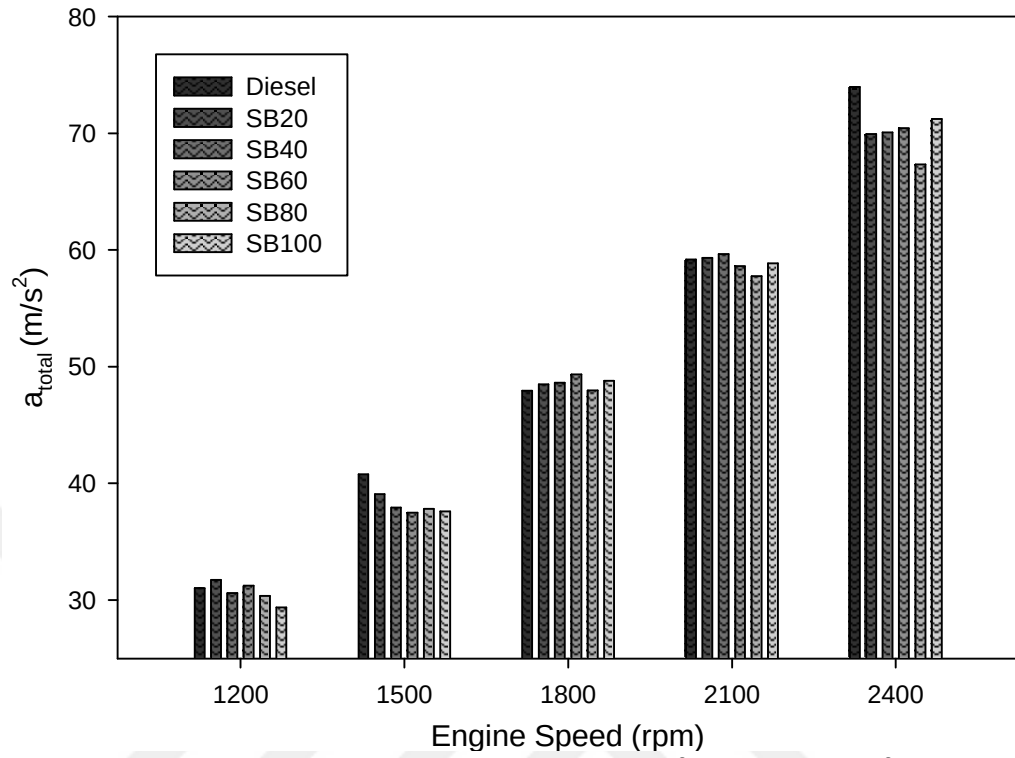


Figure 5.19. a_{total} versus engine speed when the engine fuelled with sunflower biodiesel

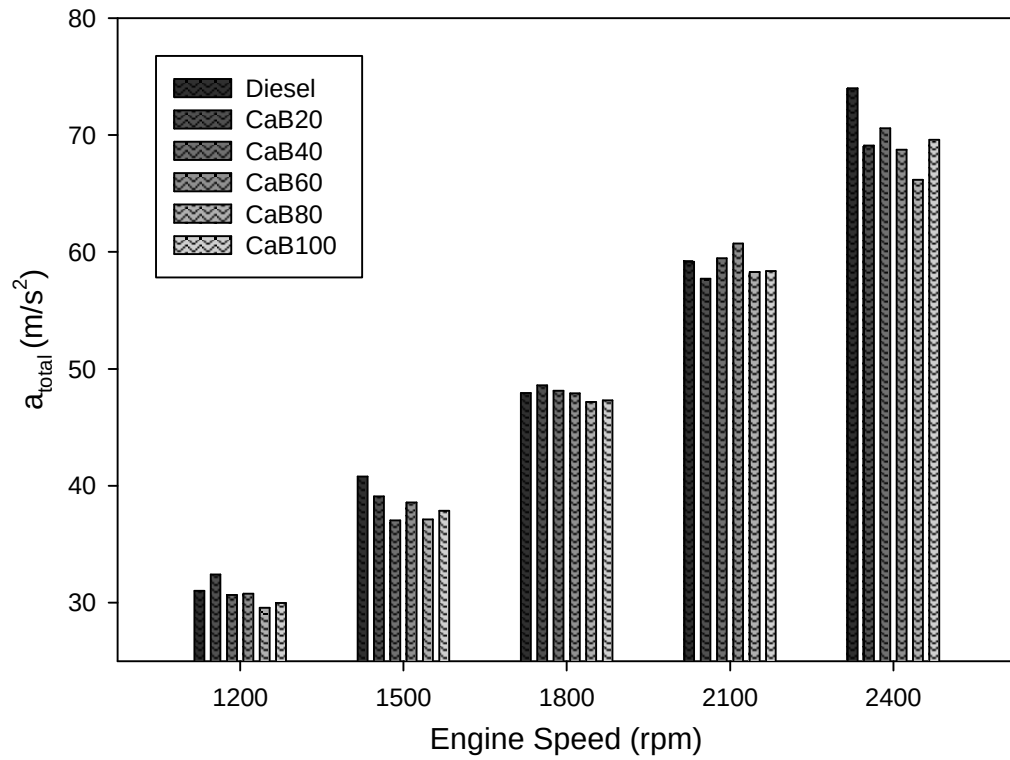


Figure 5.20. a_{total} versus engine speed when the engine fuelled with canola biodiesel

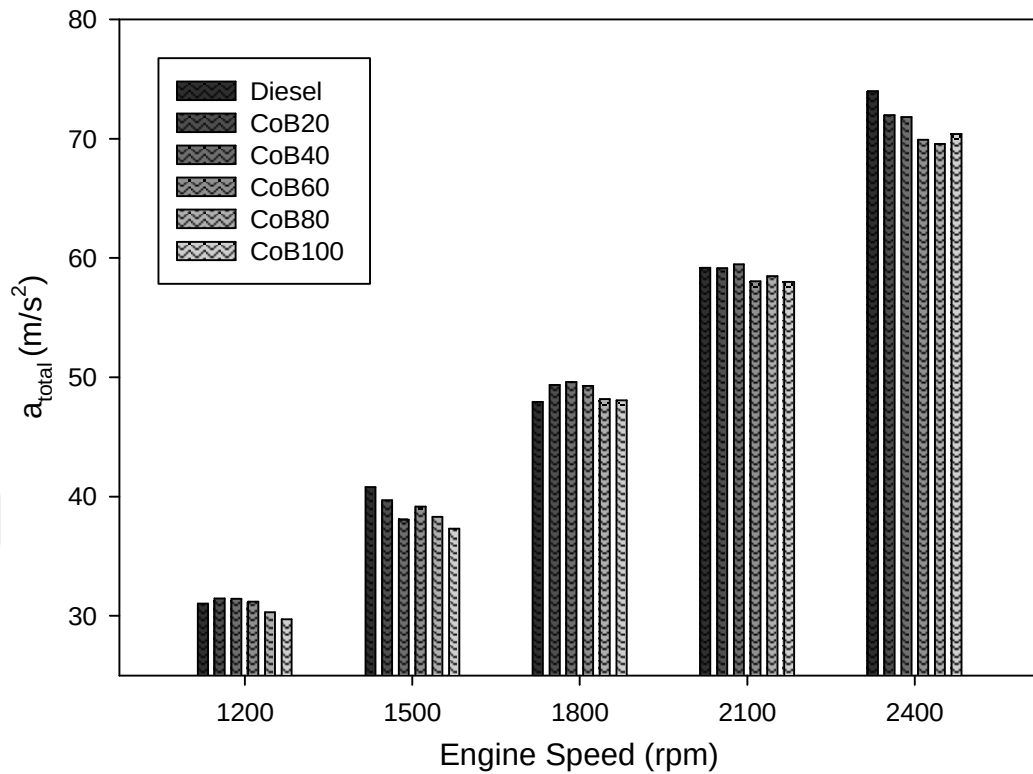


Figure 5.21. a_{total} versus engine speed when the engine fuelled with corn biodiesel

The average of engine vibration (a_{total}) decreased by 1,72%, 2,37%, 0,5% for SB20, CaB20, CoB20; 2,38%, 2,79%, 0,98% for SB40, CaB40, CoB40; 2,28%, 2,44%, 2,11% for SB60, CaB60, CoB60; 4,60%, 5,76%, 3,19% for SB80, CaB80, CoB80 and 2,80%, 3,87%, 3,72% for SB100, CaB100, CoB100, respectively compared with D100. Variations in fuel properties may explain the differences.

Since biodiesel contains extra oxygen, combustion quality of biodiesel is better than combustion of conventional diesel fuel. That's why; many researchers have concluded on that, oxides of nitrogen exhaust emission generally increases with biodiesel addition by the same reason. Enhancement of combustion with the usage of biodiesel means lowering vibration of the diesel engine block.

5.2.2.1.(2). Sound Pressure Level

The instantaneous heat release which is caused by autoignition of the whole homogeneous charge simultaneously during compression stroke. The instantaneous

heat release results in abrupt rise in temperature followed by abrupt pressure rise, and then high levels of noise. Controlling this sudden heat release is extremely important, because it is the main source of pressure rise, which may cause a severe damage to the engine (Bendu and Murugan, 2014).

Noise experiments were conducted in a sound insulated room. Furthermore, periphery of dynamometer was covered by a wooden box with sound absorber panels.

Noise is a major environmental issue, mainly in urban areas, affecting a large number of people. Most assessments of the problem of environmental noise have been based on the annoyance it causes to humans, or the extent to which it disturbs various human activities (Giakoumis et al., 2016). Therefore, A- weighted SPL, which is similar to perceived by the human ear was used in order to processing of results. The external sound field of diesel engines comprises the contribution of gas-flow, combustion and mechanical noise (Torregrosa et al., 2013; Giakoumis et al., 2011). In Figs. 5.22, 5.23, and 5.24, the results of noise measurement with diesel and biodiesel blend fuels were shown.

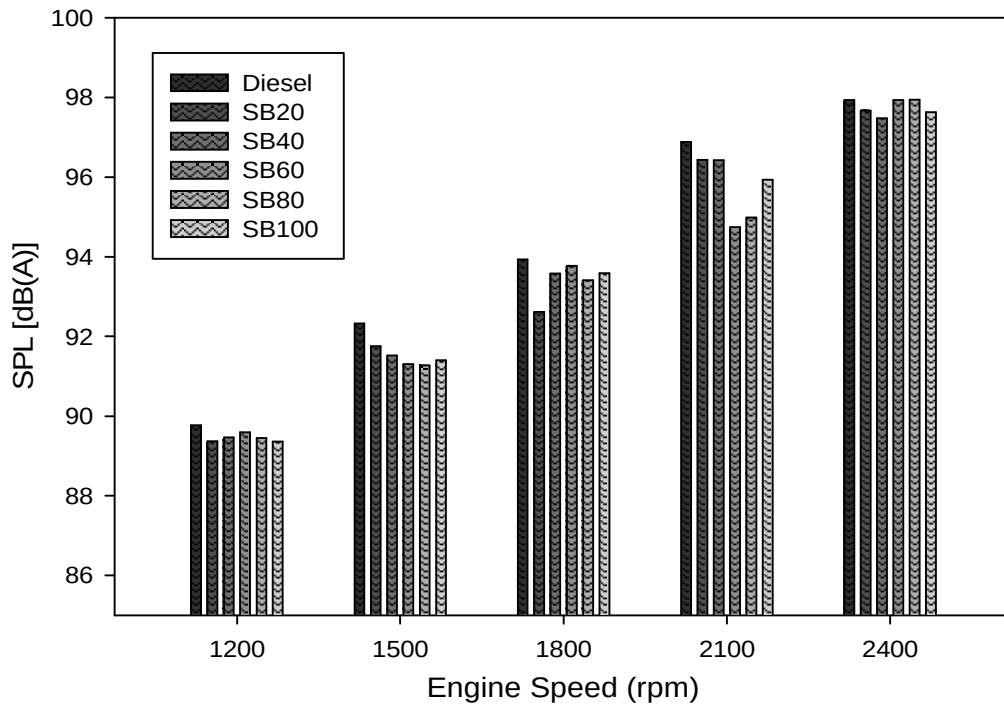


Figure 5.22. SPL versus engine speed when the engine fuelled with sunflower biodiesel

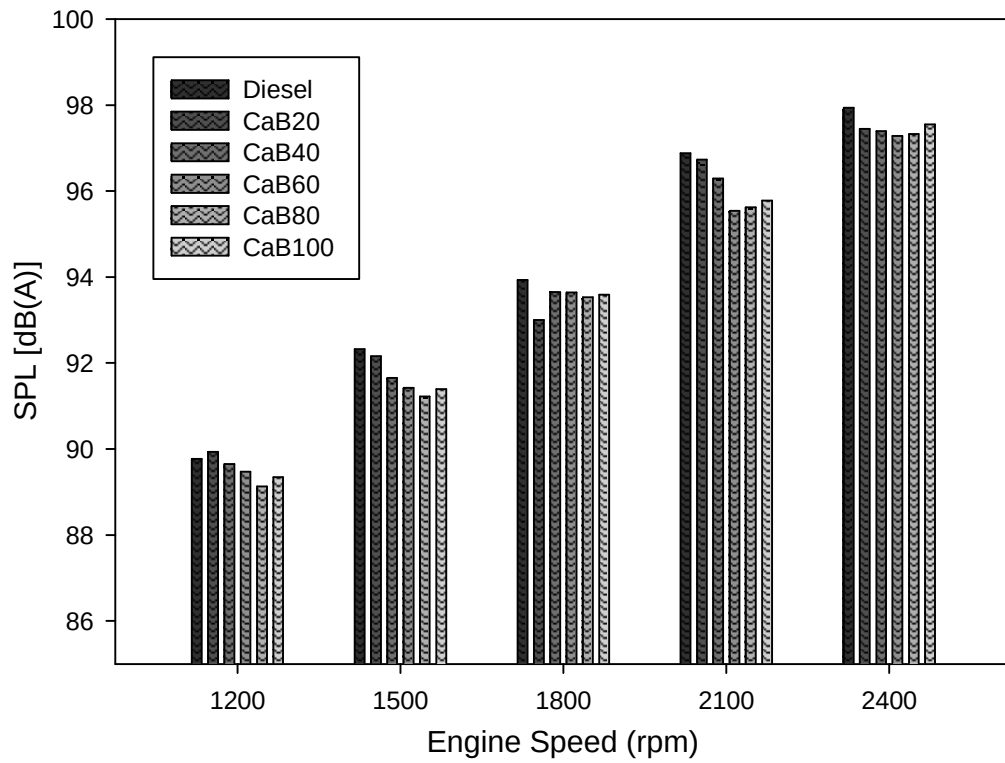


Figure 5.23. SPL versus engine speed when the engine fuelled with canola biodiesel

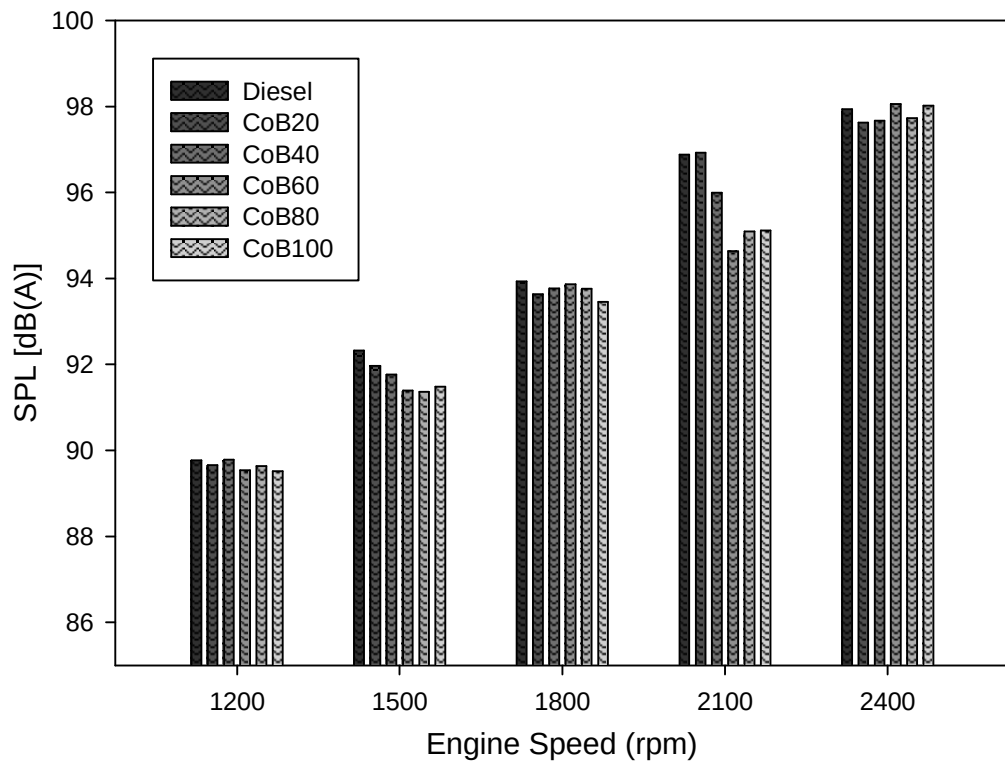


Figure 5.24. SPL versus engine speed when the engine fuelled with corn biodiesel

SPL of the engine was also increased by increasing engine speed. Average SPL found slightly lower than that of low sulphur diesel fuel with 0,6 dB[A], 0,3 dB[A], 0,2 dB[A], for SB20, CaB20, CoB20; 0,5 dB[A], 0,4 dB[A], 0,4 dB[A], for SB40, CaB40, CoB40; 0,7 dB[A], 0,7 dB[A], 0,7 dB[A], for SB60, CaB60, CoB60; 0,8 dB[A], 0,8 dB[A], 0,7 dB[A], for SB80, CaB80, CoB80; and 0,6 dB[A], 0,6 dB[A], 0,7 dB[A], for SB100, CaB100, CoB100, respectively. Decrement of SPL may be related with the decrement of engine vibration.

5.2.2.1.(3). Results of Linear and Non-Linear Regression Analysis

In this study, both linear and non-linear regression analyses were applied to experimental data on experimental engine 2.

Forecasted parameters are vibration and SPL of the internal combustion engine. Density, cetane number, viscosity and lower heating value are selected as input parameters to predict vibration and sound pressure level of engine.

SPSS which is a software package used for statistical analysis was used to perform regression analysis. Results of analysis can be seen from the following equations (5.1, 5.2, 5.3, and 5.4):

$$\begin{aligned} \text{Vibration} = & 71.126 - (19.43 * \text{density}) - (0.123 * \text{CN}) - \\ & (1.042 * \text{viscosity}) + (0.000121 * \text{LHV}) \end{aligned} \quad (5.1.)$$

$$\begin{aligned} \text{Sound Level} = & 85.097 + (10.596 * \text{density}) + (0.041 * \text{CN}) - \\ & (0,366 * \text{viscosity}) - (3.266 * 10^{-5} * \text{LHV}) \end{aligned} \quad (5.2.)$$

$$\begin{aligned} \text{Vibration} = & 35.318 * (\text{density}^{0.003}) * (\text{CN}^{-0.101}) * (\text{viscosity}^{-0.109}) * \\ & (\text{LHV}^{0.082}) \end{aligned} \quad (5.3.)$$

$$\begin{aligned} \text{Sound Level} = & \\ & 103.276 * (\text{density}^{0.127}) * (\text{CN}^{0.017}) * (\text{viscosity}^{-0.02}) * (\text{LHV}^{-0.011}) \end{aligned} \quad (5.4.)$$

Equations 5.1 and 5.2 linearly calculates vibration and SPL of engine when we put the input parameters into equation. On the other hand, equation 5.3 and 5.4 non-linearly calculates vibration and SPL of engine when we put the input parameters into equation.

The results of analysis can be seen from the following Figures 5.25 and 5.26. As seen from the figure there is good agreement between actual and predicted data. Correlation Coefficient (R) and mean absolute percentage error (MAPE) were selected as performance parameter and results are given in the following Table 5.9:

Table 5.9. Performance comparison of linear and non-linear regression.

		R	MAPE (%)
Linear	Vibration	0.784	0.747
	SPL	0.741	0.126
Non-linear	Vibration	0.814	0.689
	SPL	0.777	0.342

It can be concluded that, vibration and sound pressure level can be predicted with an acceptable accuracy with the usage of linear and non-linear regression.

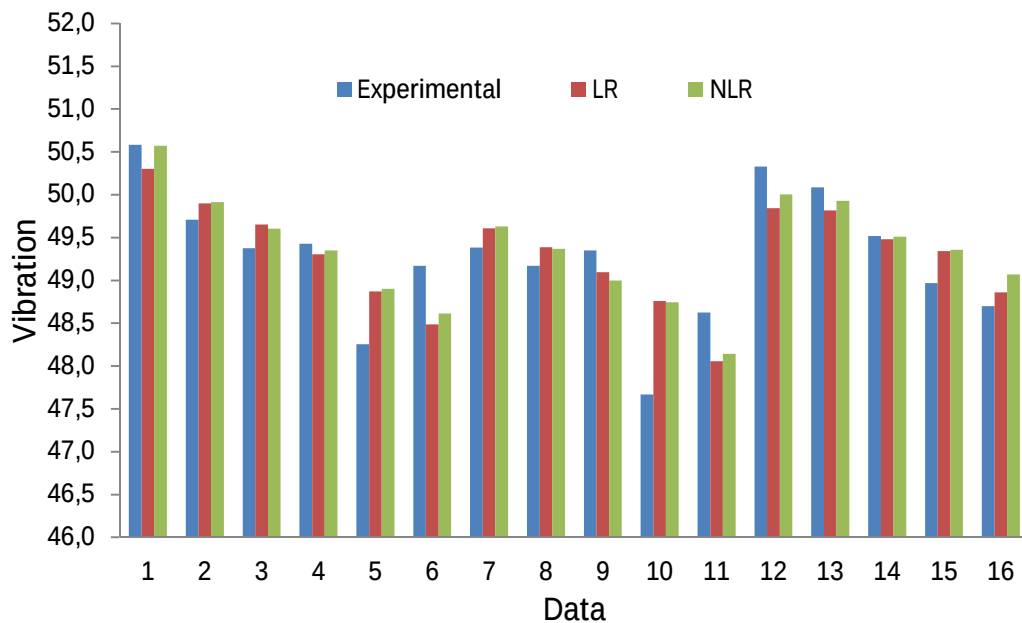


Figure 5.25. Comparison of actual and predicted vibration data

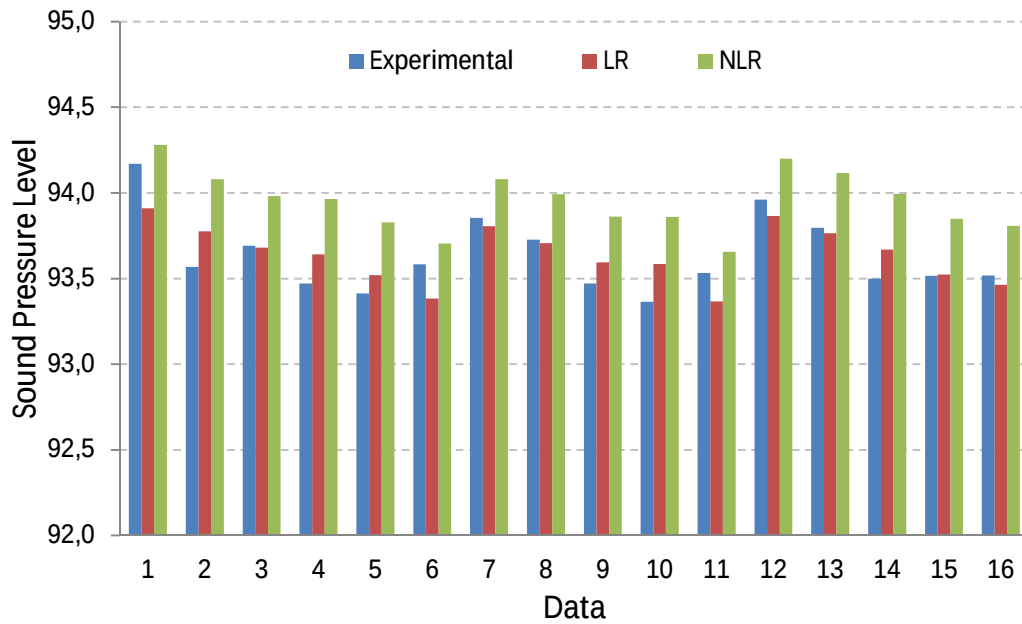


Figure 5.26. Comparison of actual and predicted SPL data

5.2.2.1.(4). Emissions

CO, CO₂ and NO_x emissions were measured throughout the experiments.

CO emissions

Incomplete combustion is the main reason of CO emission formation (Li et al., 2015). In Figures 5.27, 5.28, and 5.29 illustrate the CO values. CO emissions were decreased by using biodiesel blend since the biodiesel contains extra oxygen. Therefore, complete combustion enhanced with biodiesel usage. The average CO emission for the entire speed range for SB, CaB, and CoB were found 7,82%, 10,40%, 12,38%, 15,68%, and 18,55% (SB20, SB40, SB60, SB80, and SB100, respectively); 12,99%, 17,00%, 19,49%, 22,46%, and 24,76% (CaB20, CaB40, CaB60, CaB80, and CaB100, respectively); 4,05%, 7,63%, 10,73%, 16,48%, and 17,14% (CoB20, CoB40, CoB60, CoB80, and CoB100, respectively) lower than that of D100.

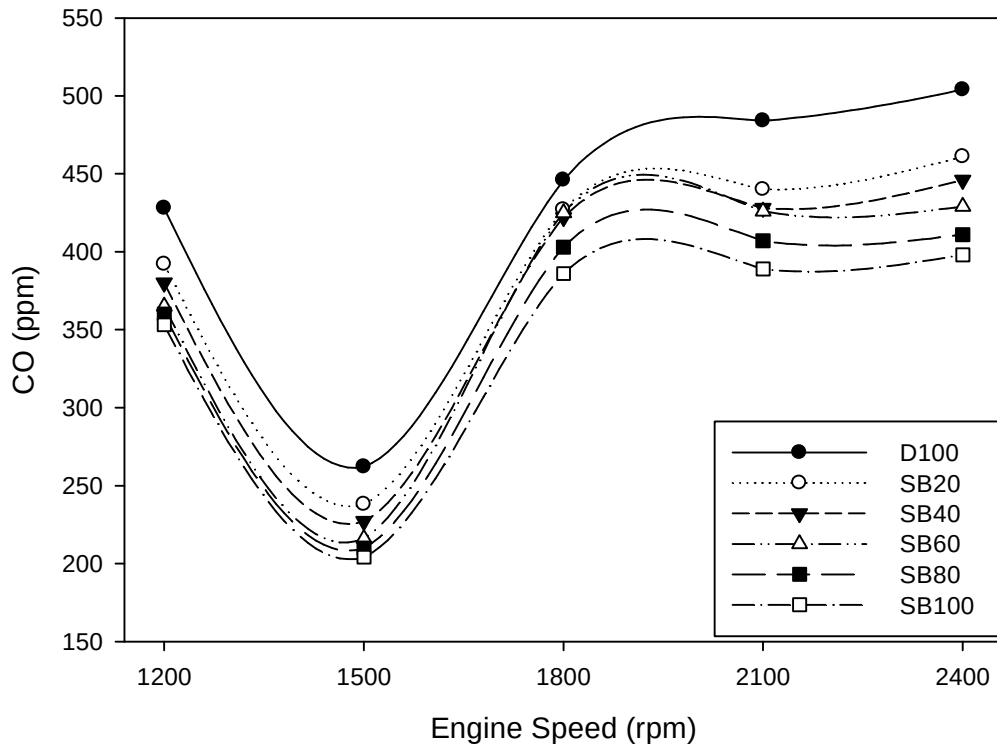


Figure 5.27. CO emission values of SB blends

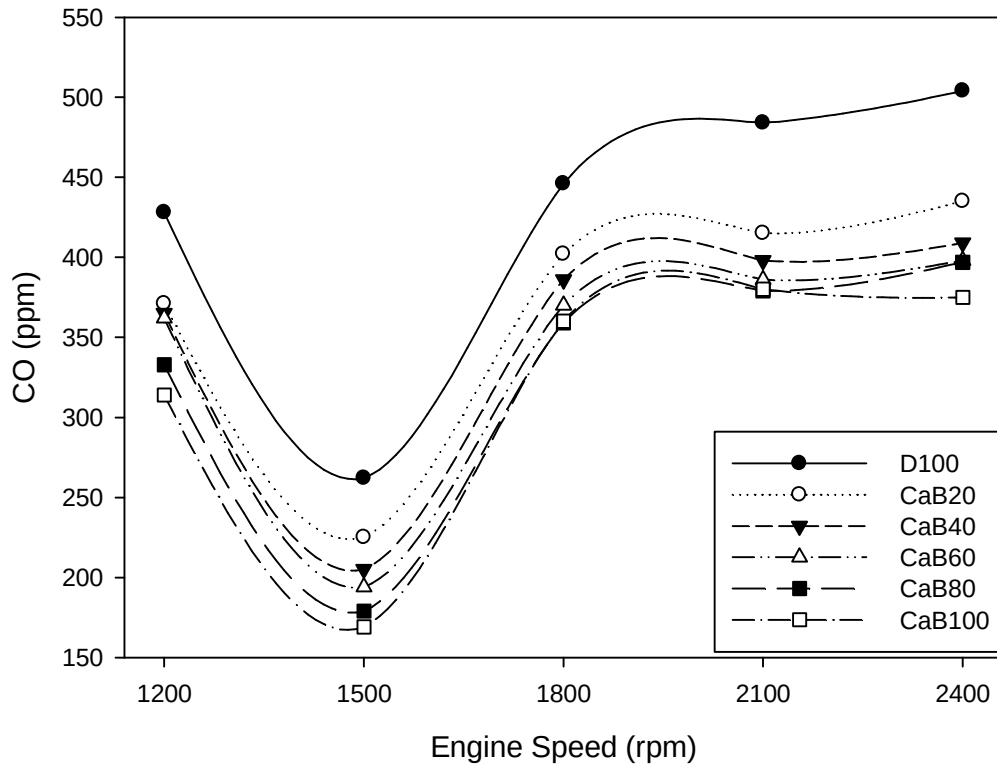


Figure 5.28. CO emission values of CaB blends

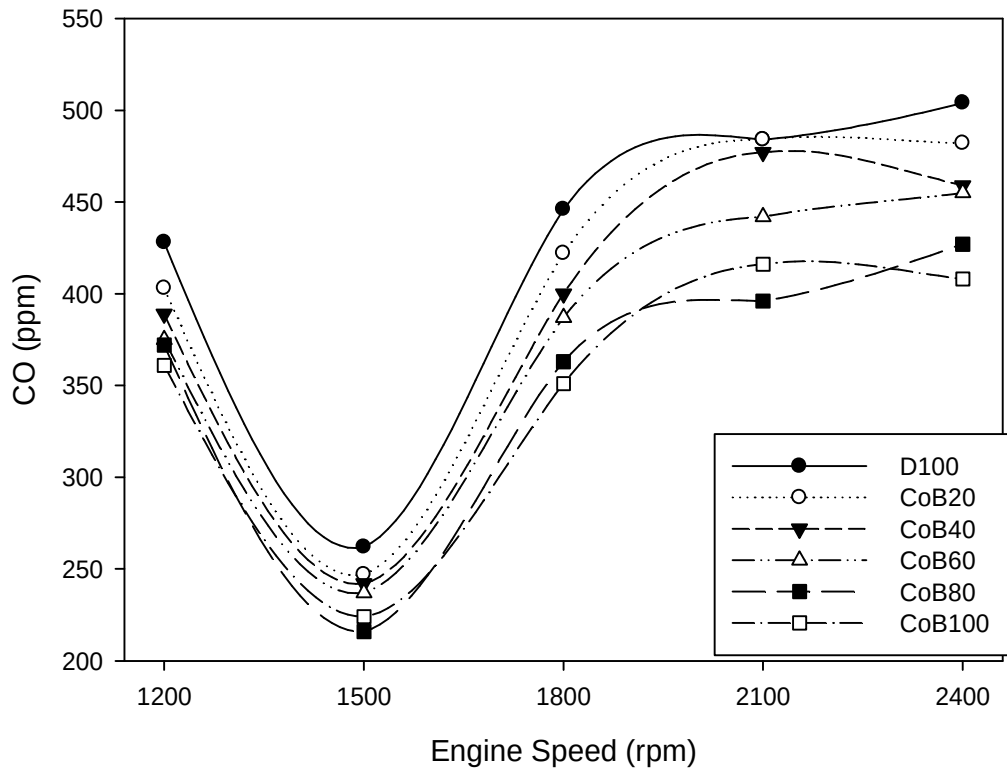
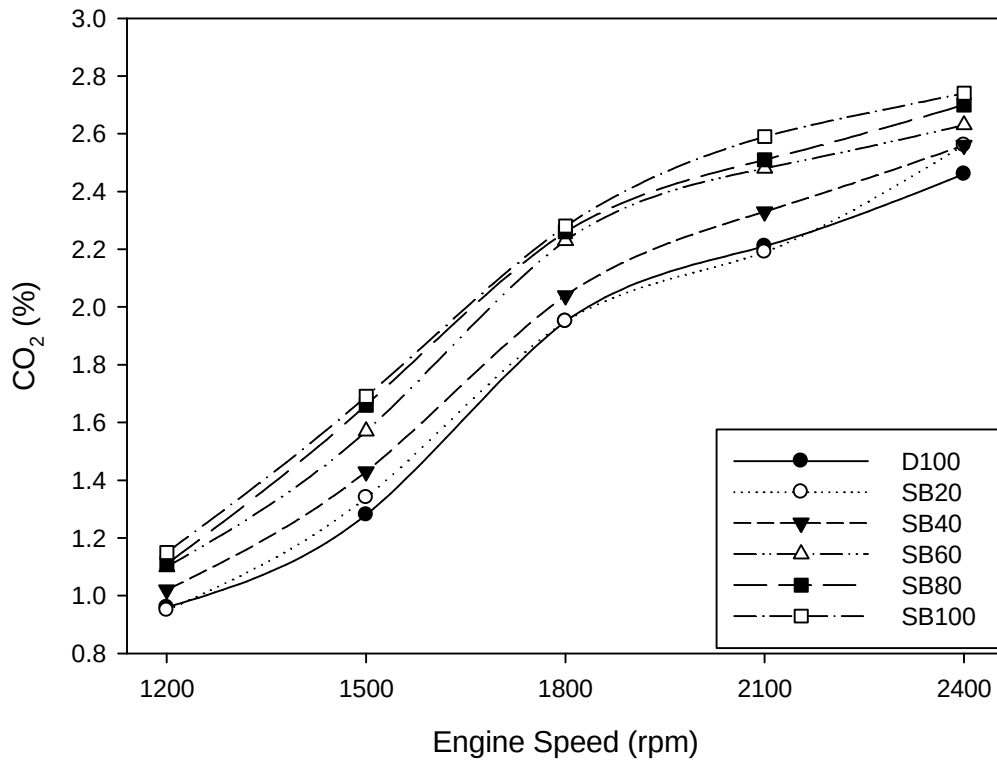
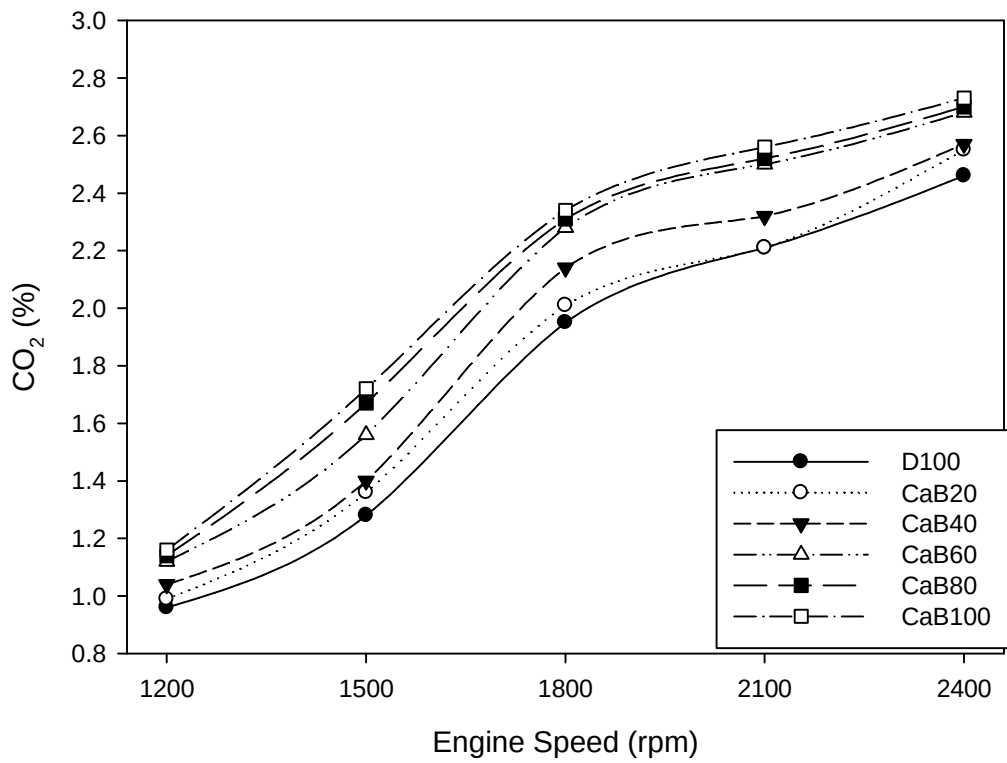


Figure 5.29. CO emission values of CoB blends

CO₂ emissions

CO₂ emission is produced by complete combustion of fuel. The concentration of CO₂ has opposite trend to that of concentration of CO owing to improvement of combustion process. Variation of CO₂ emissions of experiments were shown in figures 5.30, 5.31, and 5.32.

Compared to D100 fuel, increasing biodiesel proportion increased CO₂ emissions 1,47%, 5,87%, 12,98%, 15,58%, and 17,95% for SB; 2,93%, 6,88%, 14,45%, 16,70%, and 18,62% for CaB; 1,24%, 5,87%, 11,17%, 15,24%, and 15,69% for CoB fuels for 20%, 40%, 60%, 80%, and 100% volumetric ratio of biodiesel.

Figure 5.30. CO₂ emission values of SB blendsFigure 5.31. CO₂ emission values of CaB blends

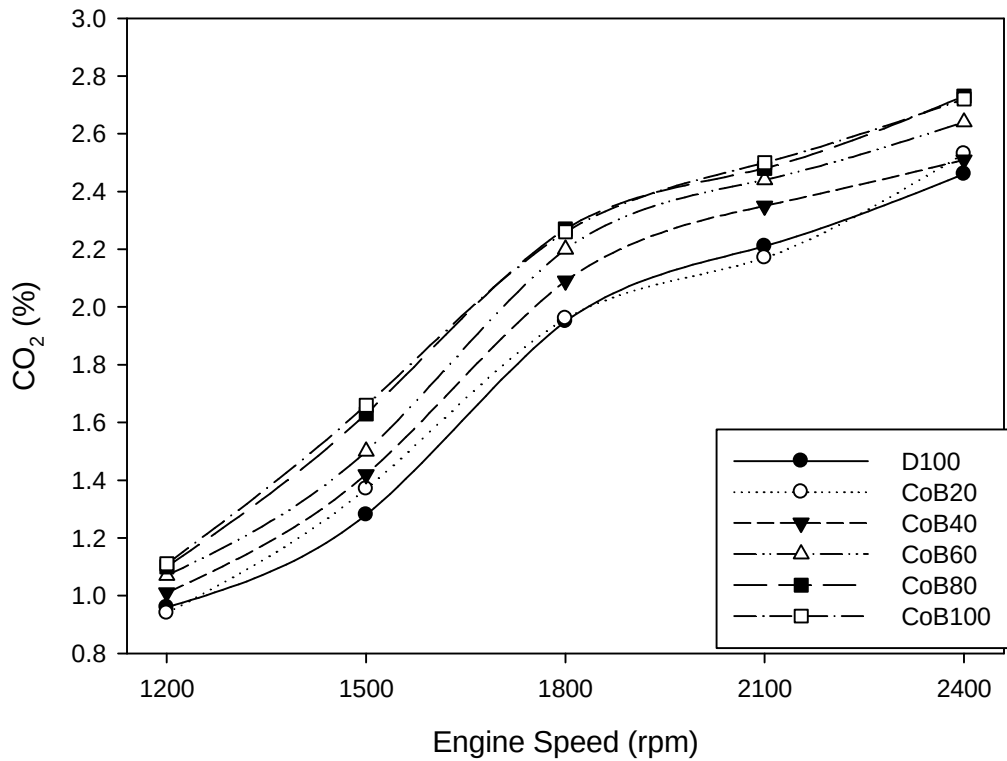
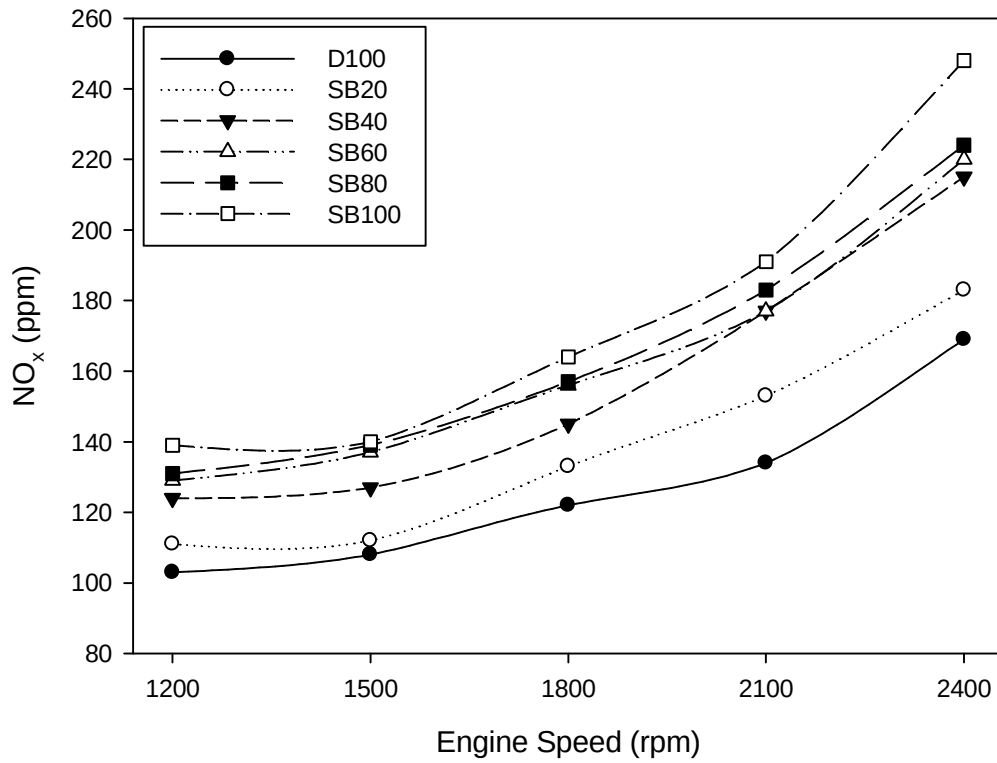
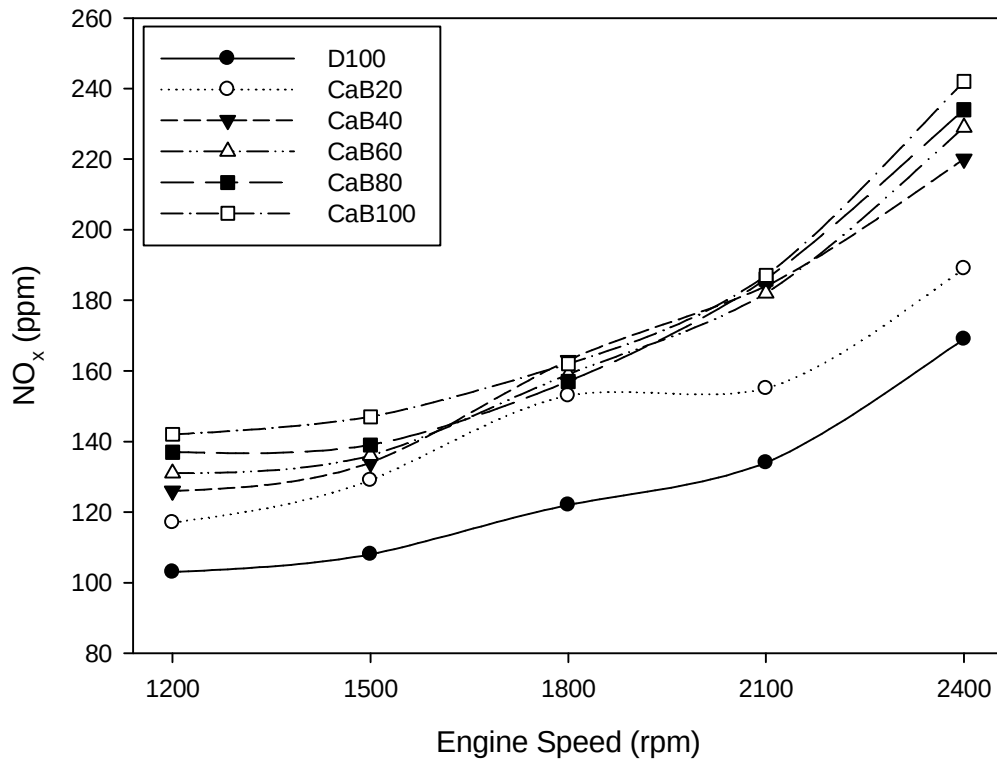


Figure 5.32. CO₂ emission values of CoB blends

NO_x emissions

NO_x is the most detrimental pollutant at the combustion stage. It is very familiar that the higher combustion temperature, longer combustion duration inside the combustion chamber and ample local oxygen concentration are the main factors for NO_x formation (Velmurugan and Sathiyagnanam, in press).

Usage of biodiesel increased NO_x emissions 4,69%, 19,21%, 23.90%, 26,17%, and 33,43% for SB20, SB40, SB60, SB80 and SB100; 12,41%, 25,11%, 26,63%, 29,05% and 33,13% for CaB20, CaB40, CaB60, CaB80 and CaB100; 4,08%, 18,00%, 22,54%, 23,60, and 27,69% for CoB20, CoB40, CoB60, CoB80 and CoB100, respectively that of D100.

Figure 5.33. NO_x emission values of SB blendsFigure 5.34. NO_x emission values of CaB blends

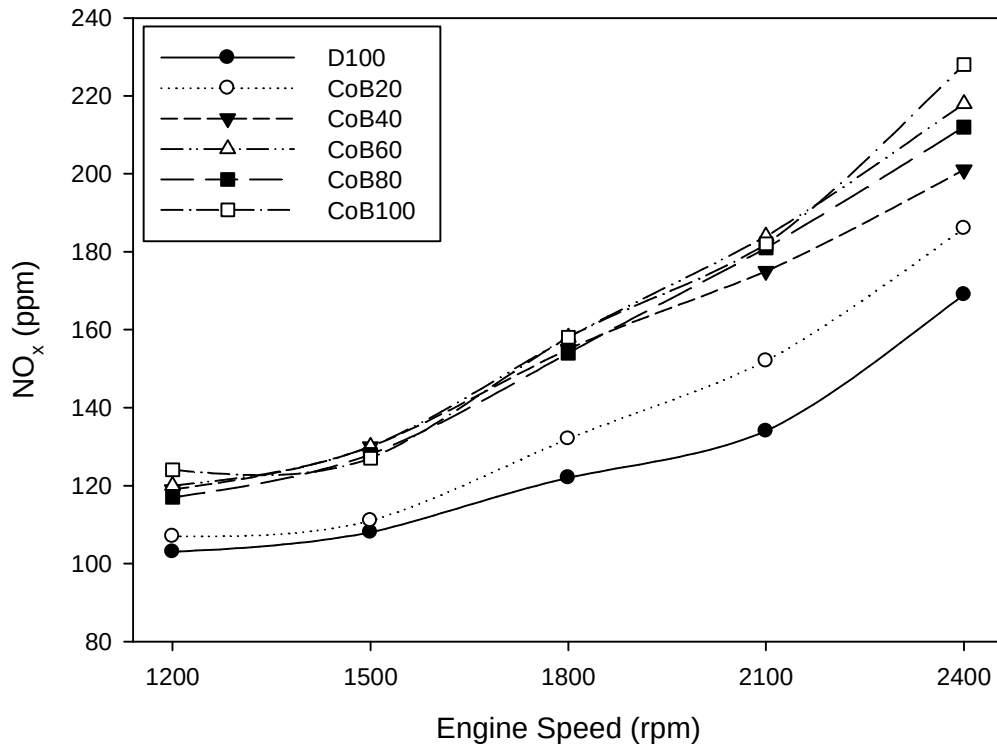


Figure 5.35. NO_x emission values of CoB blends

5.2.2.2. Compressed Natural Gas

During the experiments test engine was also fuelled CNG and seven different diesel-biodiesel fuel blends. These are pure low sulphur diesel (D100), 80% diesel, 20% sunflower biodiesel (SB20), 60% diesel, 40% sunflower biodiesel (SB40), 80% diesel, 20% canola biodiesel (CaB20), 60% diesel, 40% canola biodiesel (CaB40), 80% diesel, 20% corn biodiesel (CoB20), 60% diesel, 40% corn biodiesel (CoB40) by volume and each of them was tested with four different natural gas flow rate (NG0, NG5, NG10, and NG15) at five different engine speed (1200 rpm, 1500 rpm, 1800 rpm, 2100 rpm, and 2400 rpm) with no load condition in order to eliminate the effect of dynamometer loading mechanism.

5.2.2.2.(1). Vibration

Time domain and vibration acceleration spectrum characteristics of some experiments at x- y- z axes were presented in figure 5.36, 5.37, 5.38 and 5.39. The figures represent CoB20-NG0, CoB20-NG5, CoB20-NG10, and CoB20-NG15 at 1500 rpm, respectively and first column belong to data of x- axis, second column represents y- axis and the last column represents z- axis.

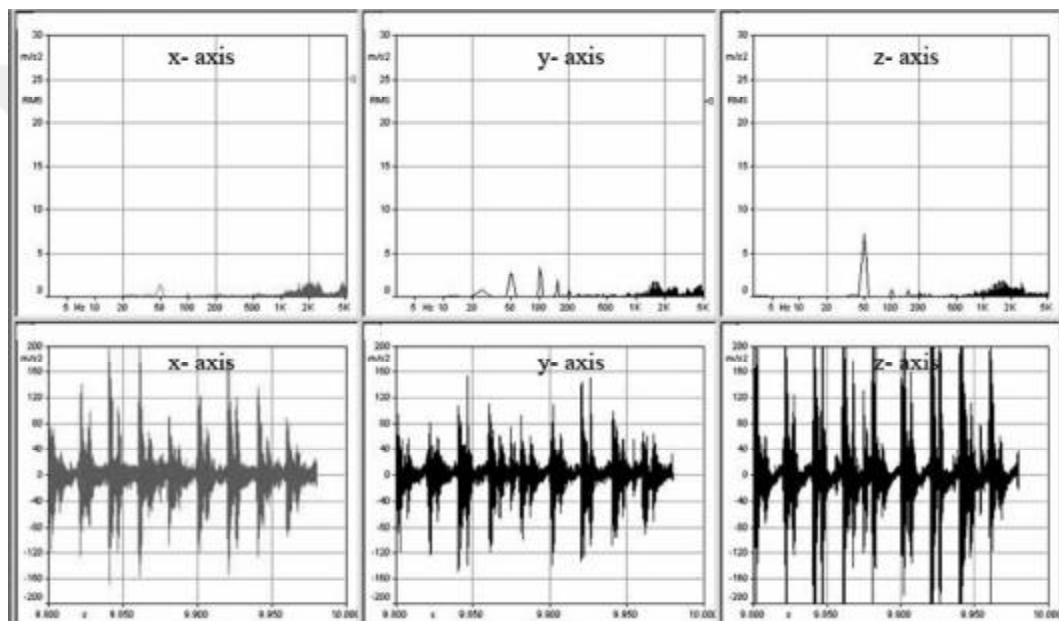


Figure 5.36. Time and frequency domain at x- y- z axes (CoB20-NG0)

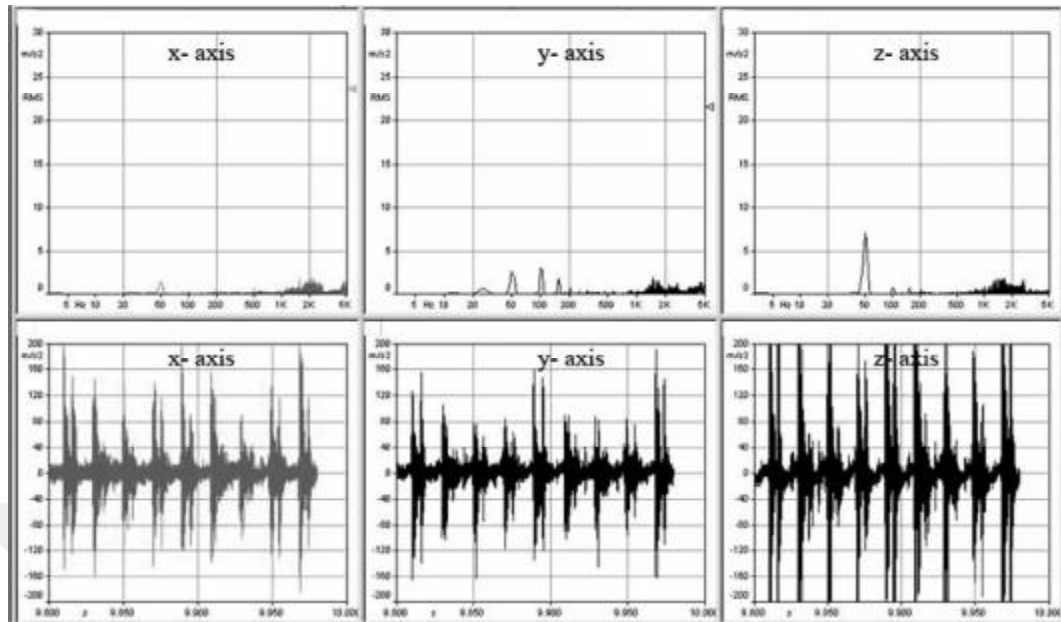


Figure 5.37. Time and frequency domain at x- y- z axes (CoB20-NG5)

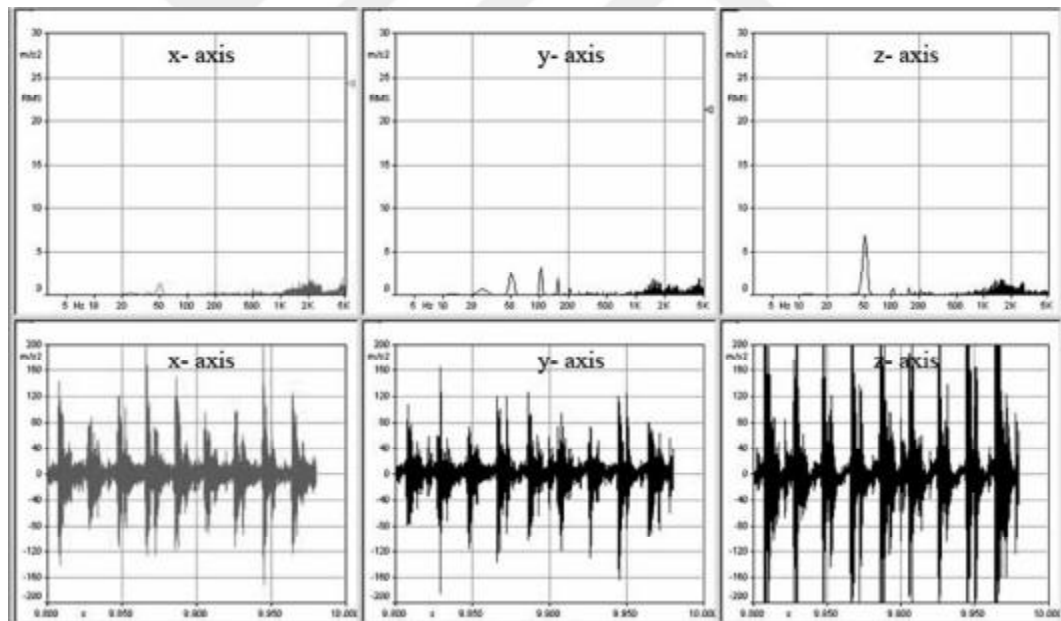


Figure 5.38. Time and frequency domain at x- y- z axes (CoB20-NG10)

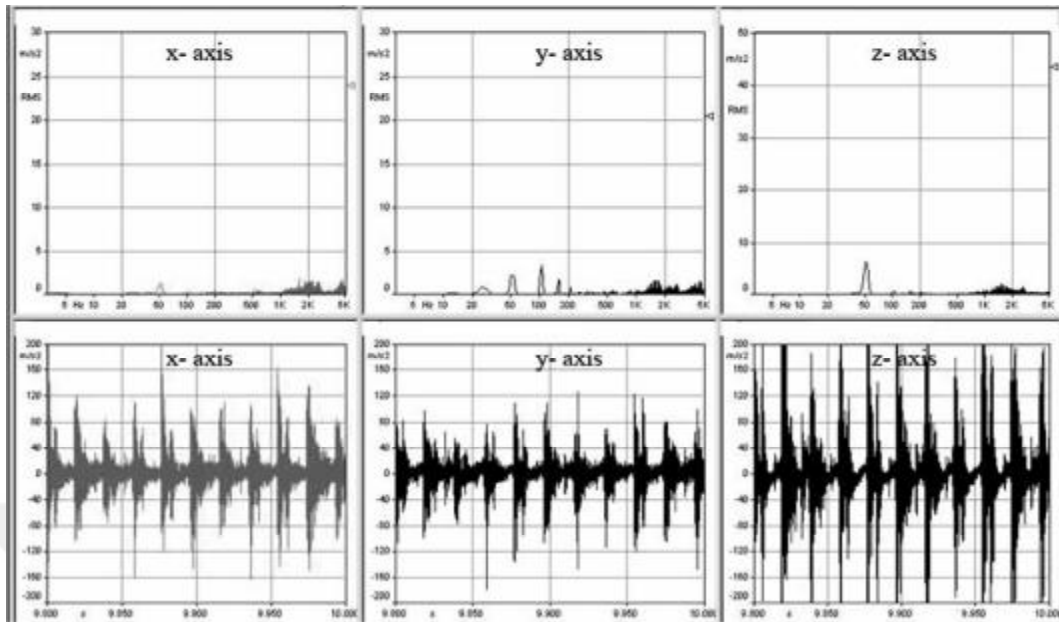


Figure 5.39. Time and frequency domain at x- y- z axes (CoB20-NG15)

The results revealed that vibration of engine block increased with engine speed. It should be primarily pointed out that with the use of each test fuel; vibration of engine block was decreased with increasing CNG flow rate. The variability of a_{total} values was examined to identify the effect of test fuels. Compared to low sulphur diesel fuel, biodiesel blends were decreased engine vibration as it mentioned in biodiesel section.

Introduction of CNG decreased vibration acceleration averagely as 2.7%, 5.5%, and 8.1% for NG5, NG10, and NG15, respectively compared to NG0. The comparison of test results were presented in figure 5.41, 5.42, 5.43, 5.44, and 5.45 at the engine speeds of 1200 rpm, 1500 rpm, 1800 rpm, 2100 rpm, and 2400 rpm, respectively.

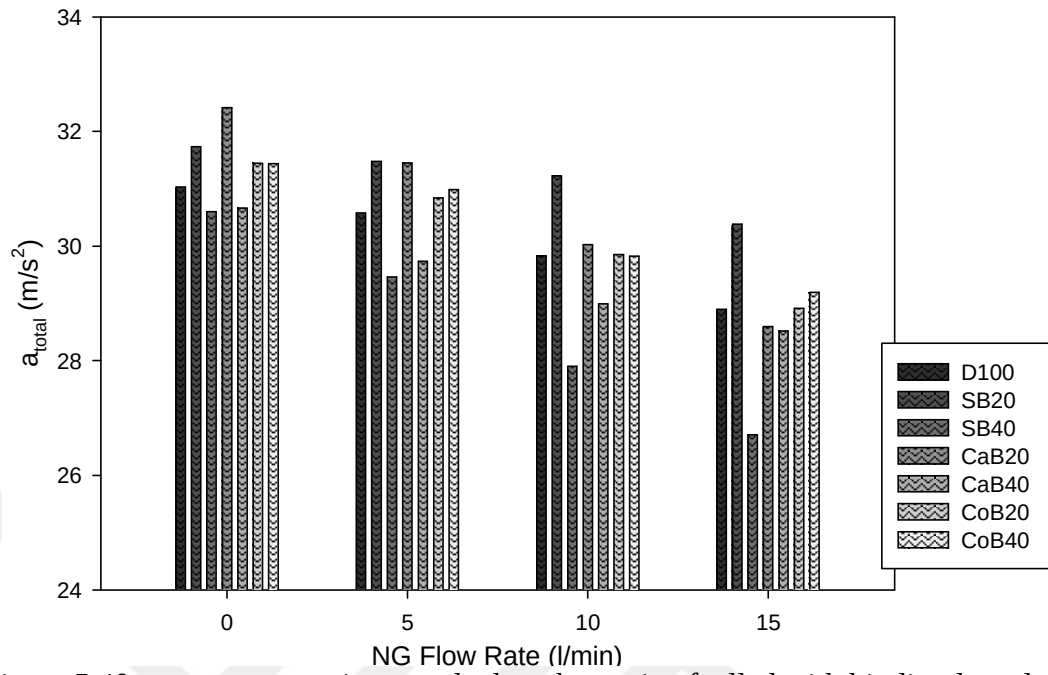


Figure 5.40. a_{total} versus engine speed when the engine fuelled with biodiesels and CNG at 1200 rpm

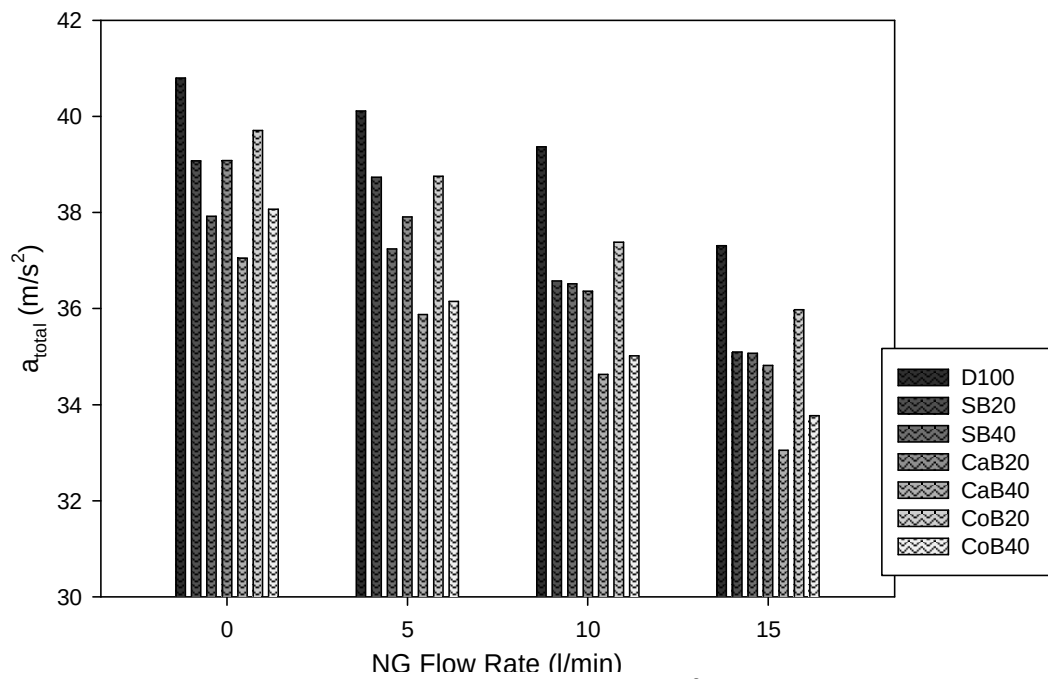


Figure 5.41. a_{total} versus engine speed when the engine fuelled with biodiesels and CNG at 1500 rpm

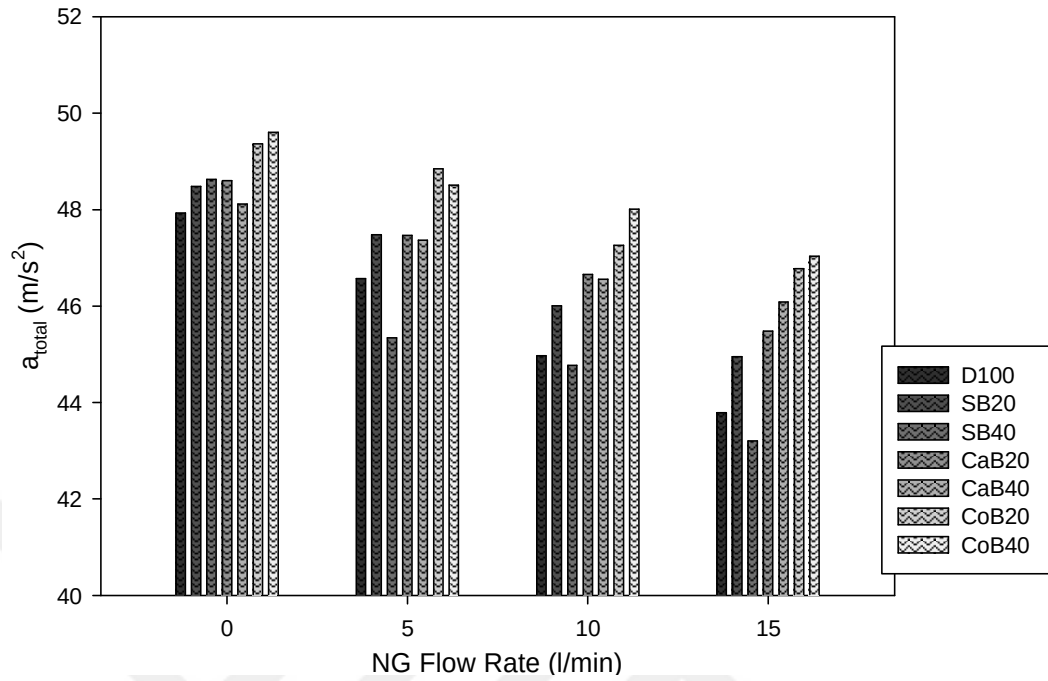


Figure 5.42. a_{total} versus engine speed when the engine fuelled with biodiesels and CNG at 1800 rpm

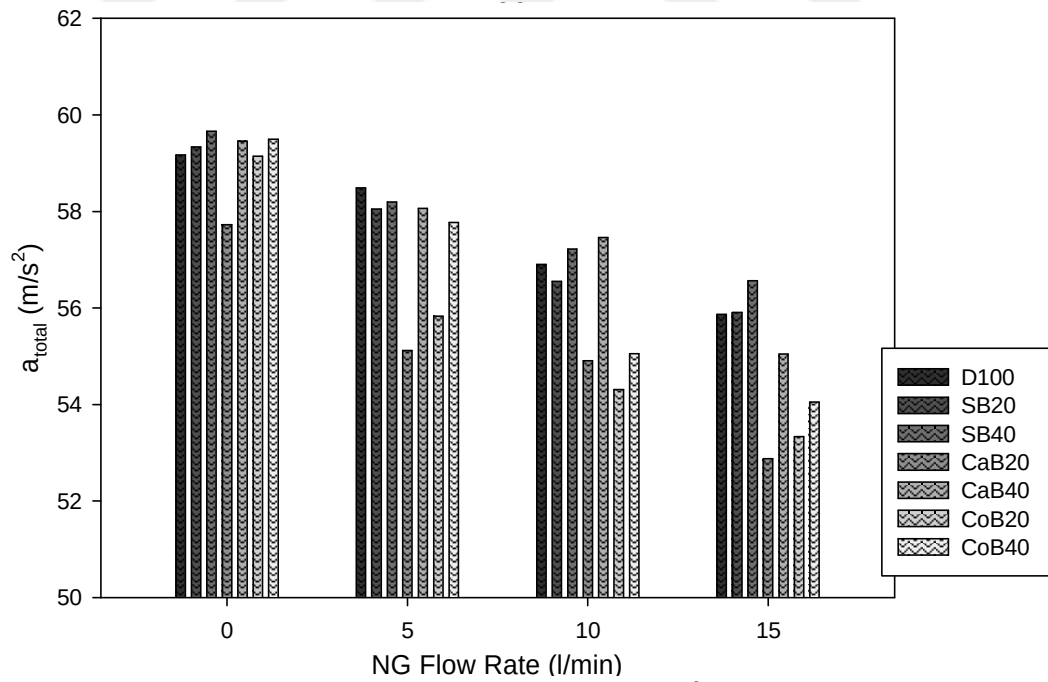


Figure 5.43. a_{total} versus engine speed when the engine fuelled with biodiesels and CNG at 2100 rpm

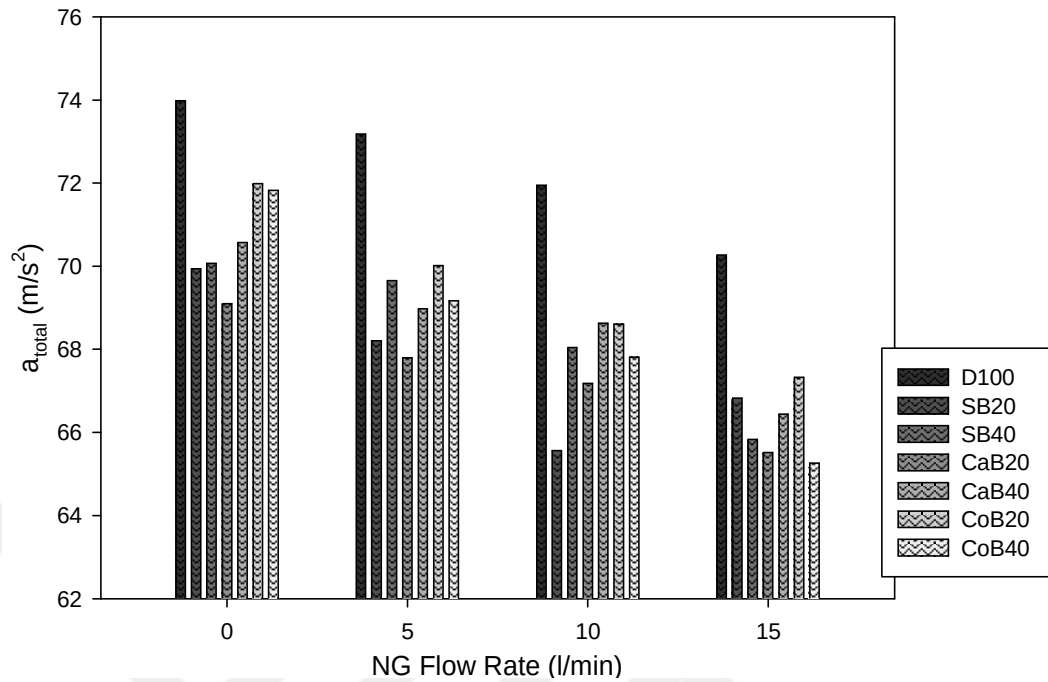


Figure 5.44. a_{total} versus engine speed when the engine fuelled with biodiesels and CNG at 2400 rpm

5.2.2.2.(2). Sound Pressure Level

Addition of CNG has also caused decrement of SPL of the engine. This expected phenomenon is maybe the result of decrement of engine vibration. Averagely NG addition into intake air was decreased the SPL by 0,2 dB(A), 0,4 dB(A), 0,5 dB(A) for NG5, NG10, and NG15, respectively compared to non-NG addition.

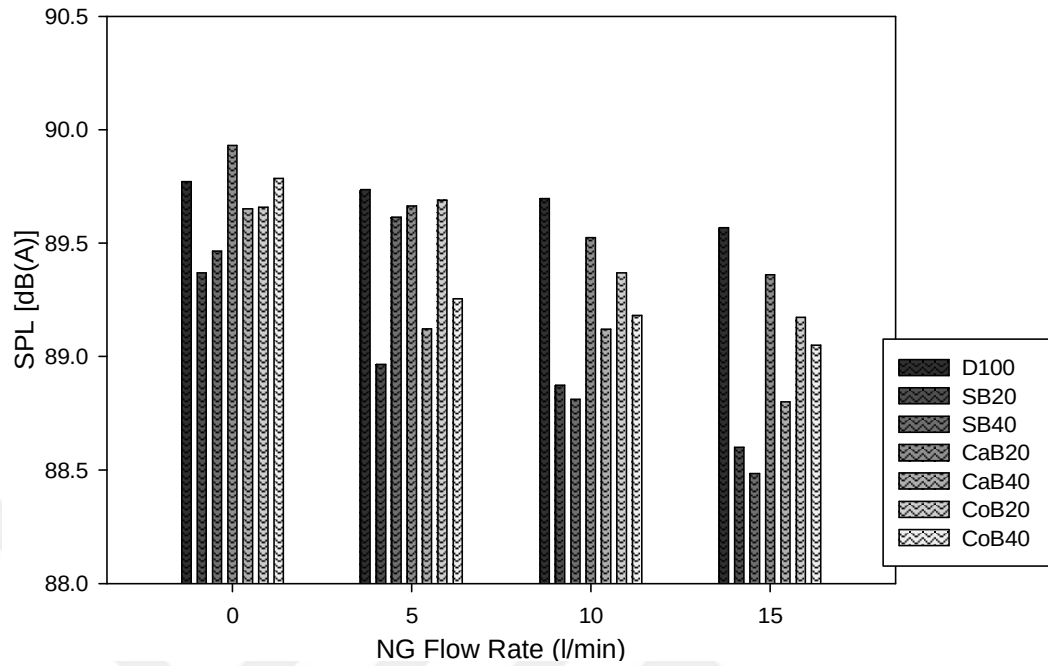


Figure 5.45. SPL versus engine speed when the engine fuelled with biodiesels and CNG at 1200 rpm

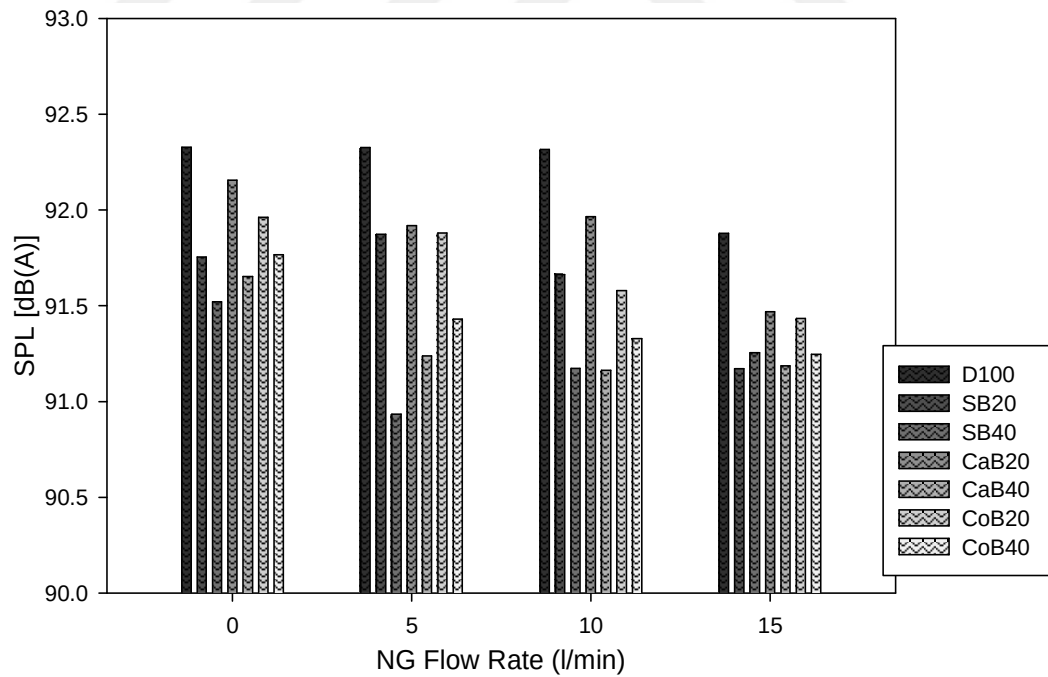


Figure 5.46. SPL versus engine speed when the engine fuelled with biodiesels and CNG at 1500 rpm

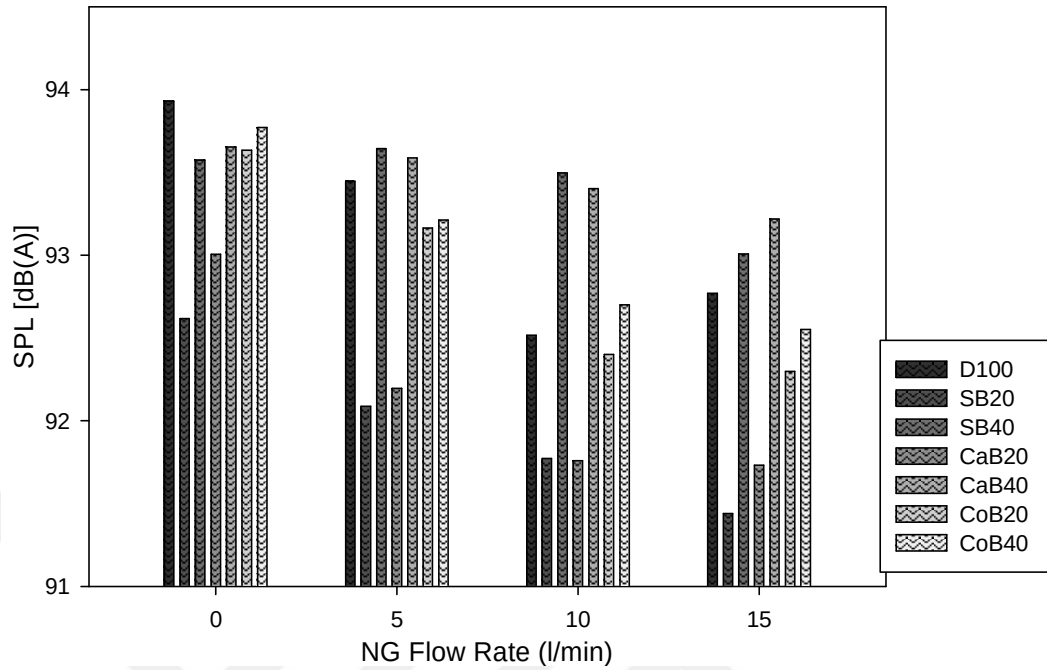


Figure 5.47. SPL versus engine speed when the engine fuelled with biodiesels and CNG at 1800 rpm

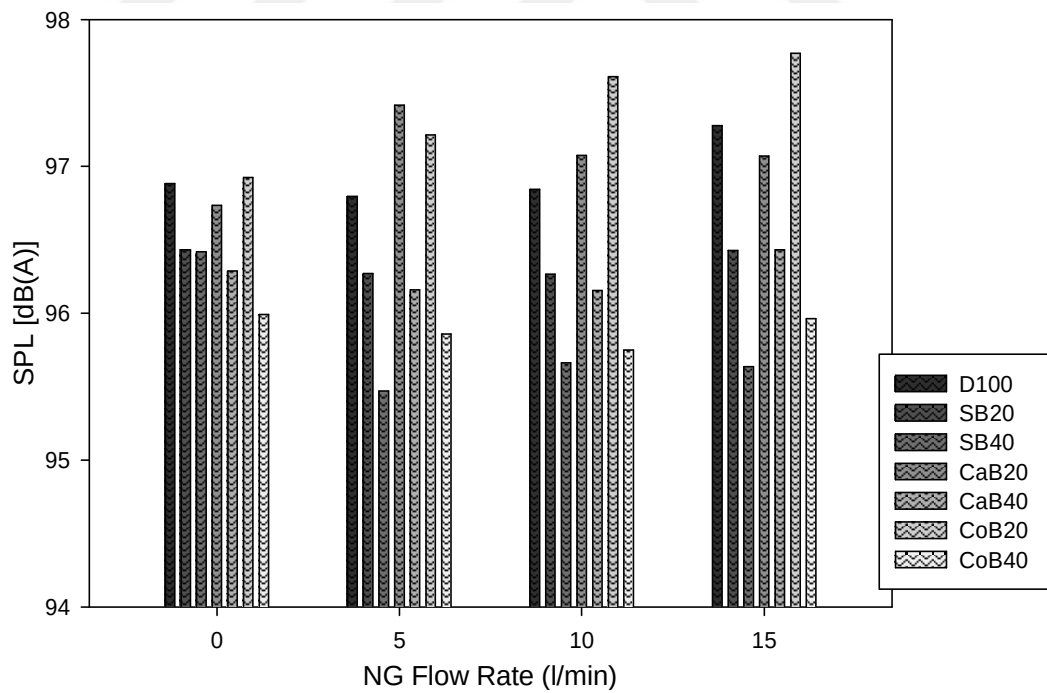


Figure 5.48. SPL versus engine speed when the engine fuelled with biodiesels and CNG at 2100 rpm

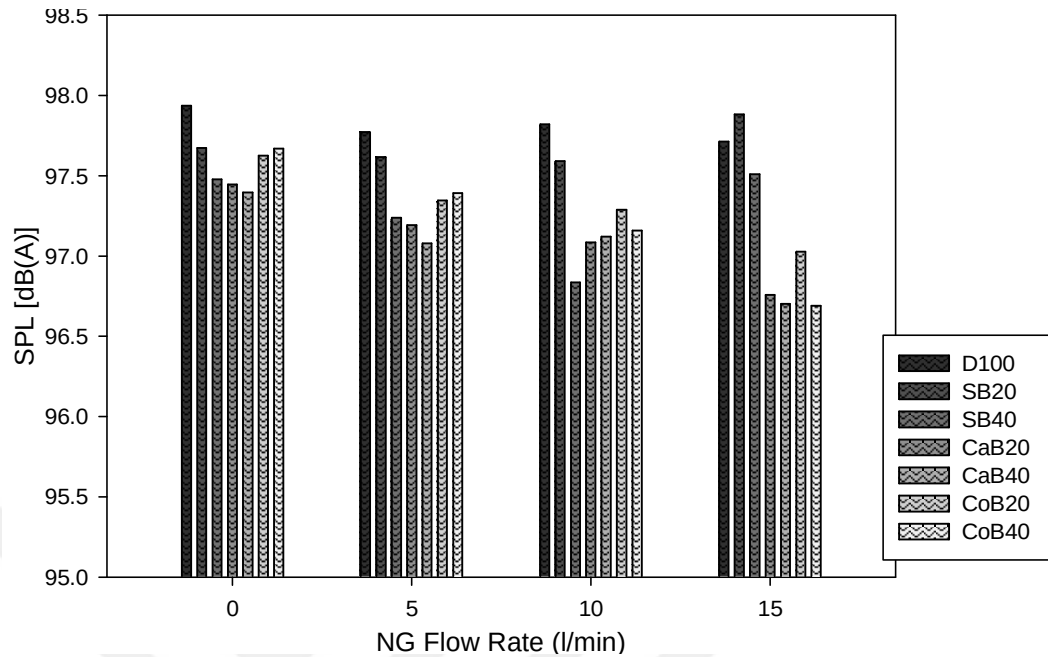


Figure 5.49. SPL versus engine speed when the engine fuelled with biodiesels and CNG at 2400 rpm

5.2.2.2.(1). Emission

CO emissions

CNG addition has greatly increased CO emissions. 26%, 55,8%, and 83,6% increment were measured with NG5, NG10, and NG15, respectively that of NG0. This is due to replacement of intake air by CNG, which reduces the possibility of complete oxidation of carbon molecules and produces CO (Paul et al., 2014).

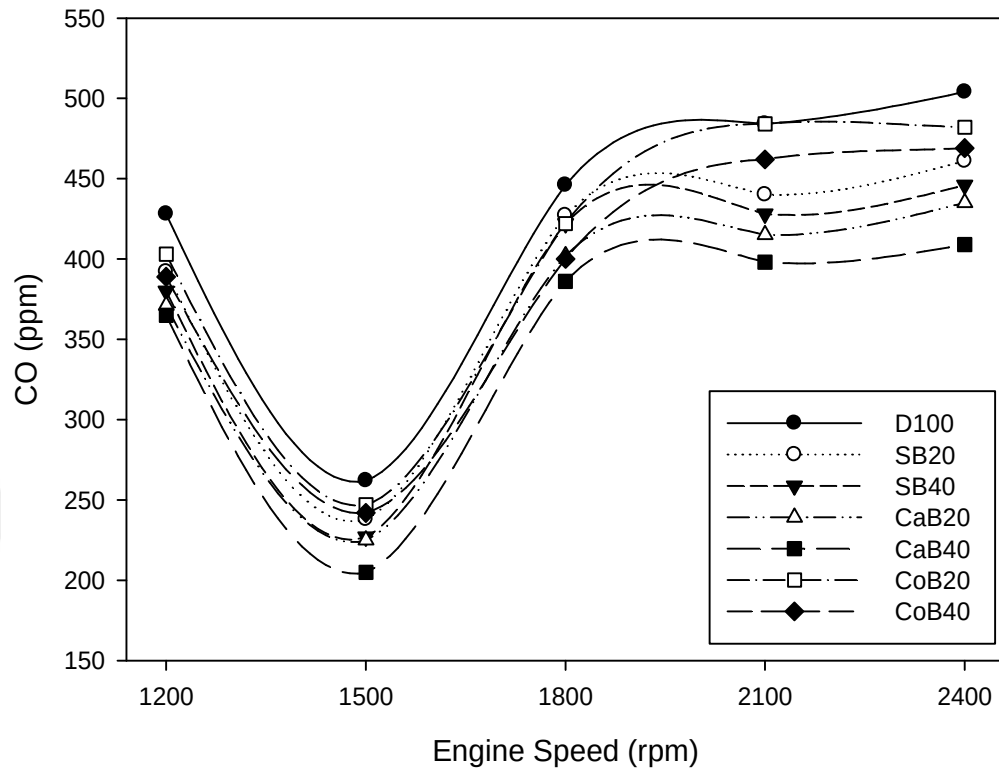


Figure 5.50. CO emission values without NG addition

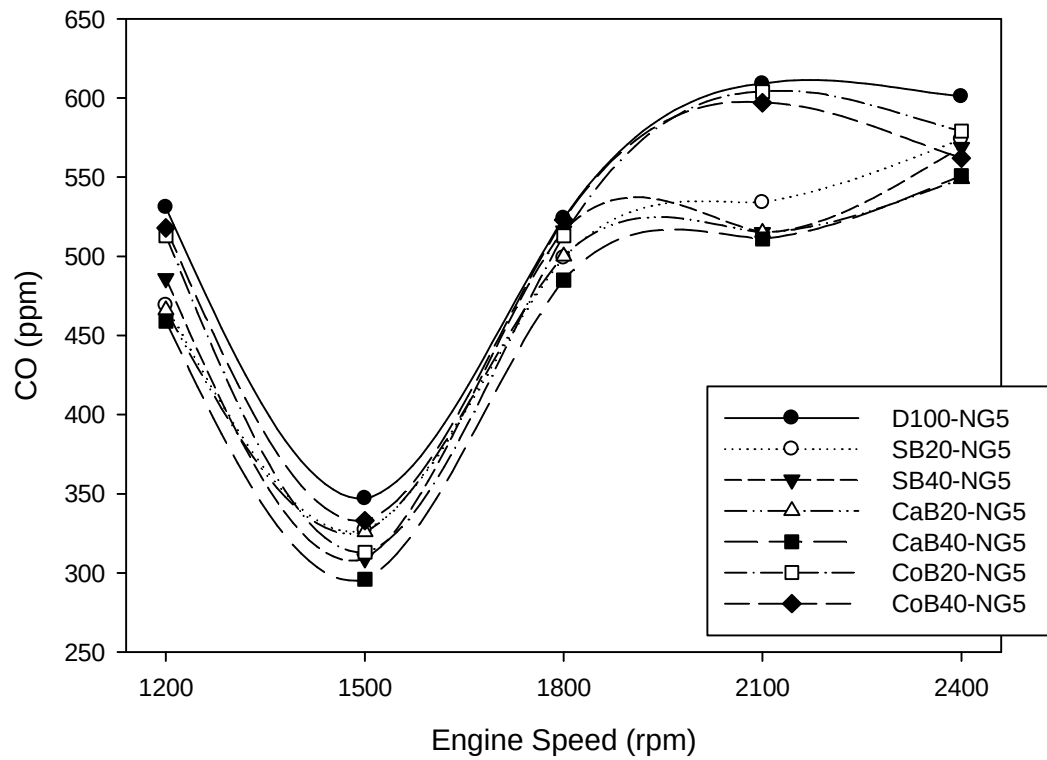


Figure 5.51. CO emission values with NG5 addition

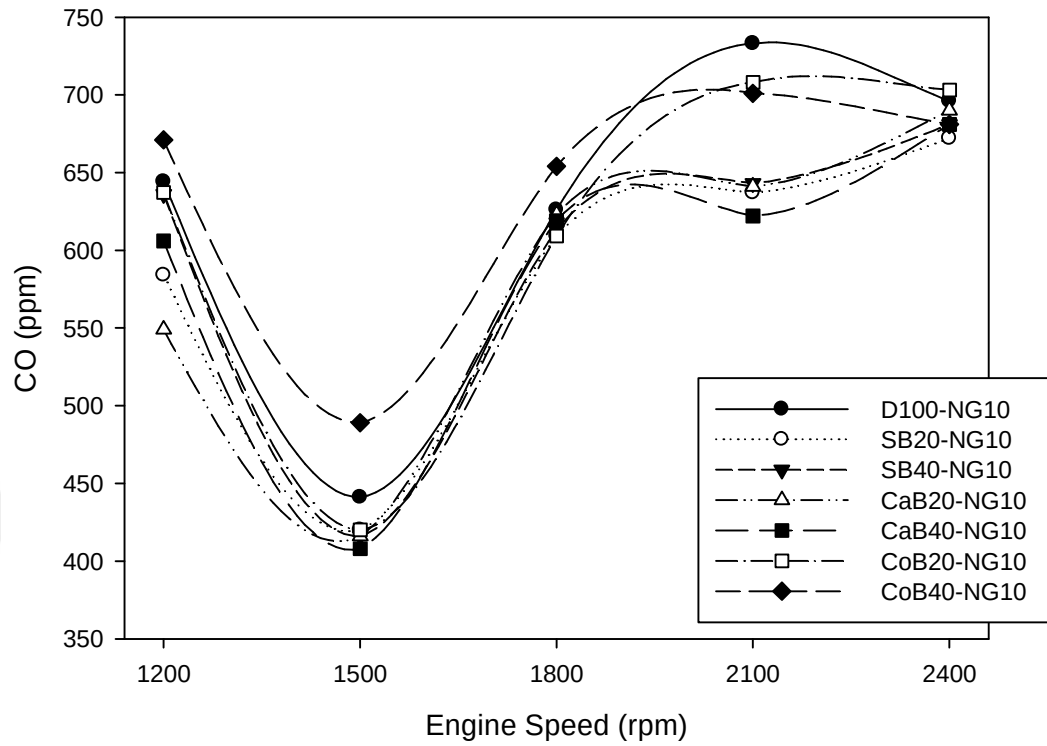


Figure 5.52. CO emission values with NG10 addition

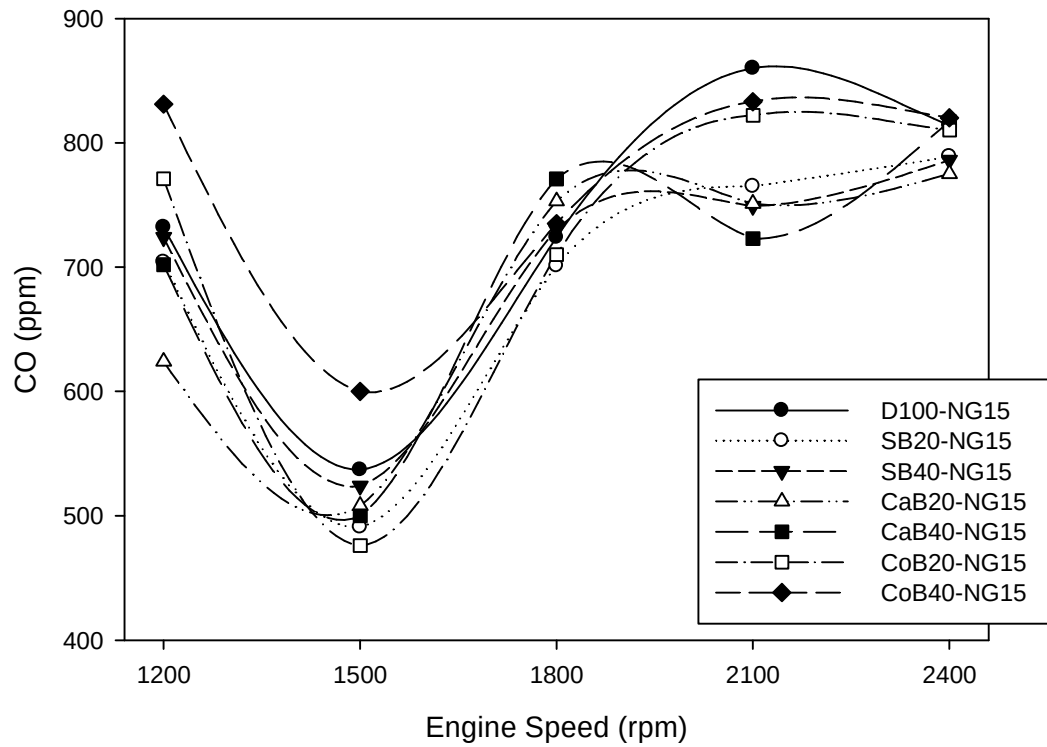


Figure 5.53. CO emission values with NG15 addition

CO₂ emissions

CO₂ emission was decreased 1,5%, 2,7%, and 4,1% with addition of NG5, NG10, and NG15 compared to NG0. CO₂, which is a product of complete combustion, is the main source for global warming and ozone layer depletion. CO₂ can be used as an indicator of combustion efficiency. However, natural gas, mainly composed of methane, has one of the lowest values of hydrogen-to-carbon ratio among hydrocarbons, making it a potential lower CO₂ emission than pure diesel fuel (Tarabet et al, 2014).

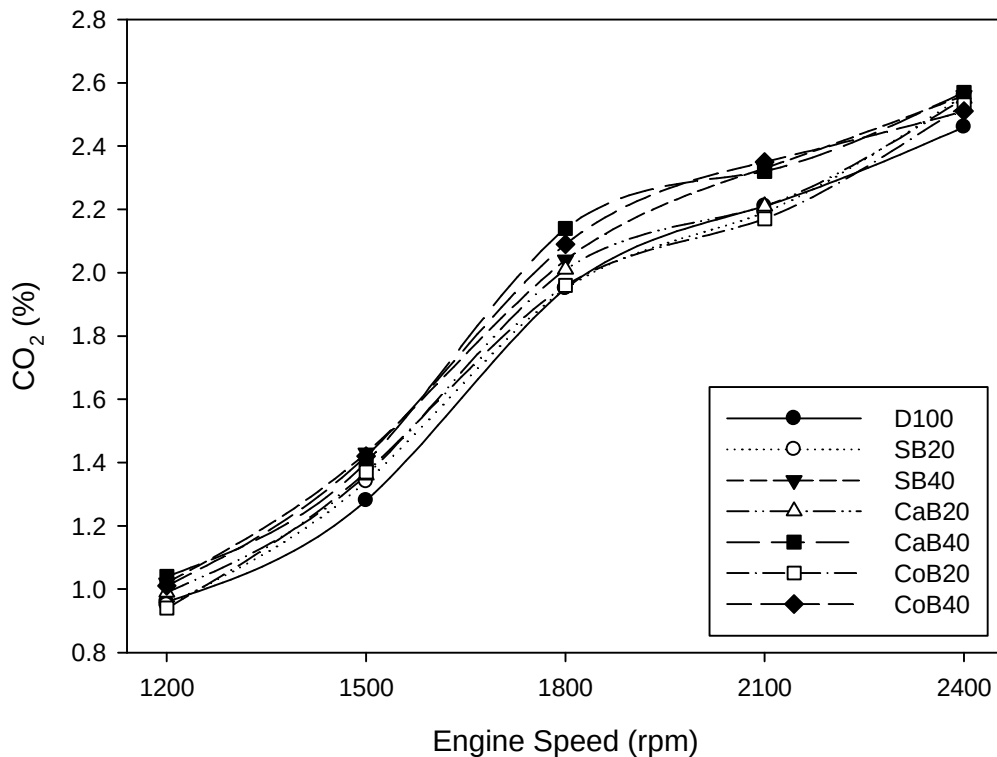
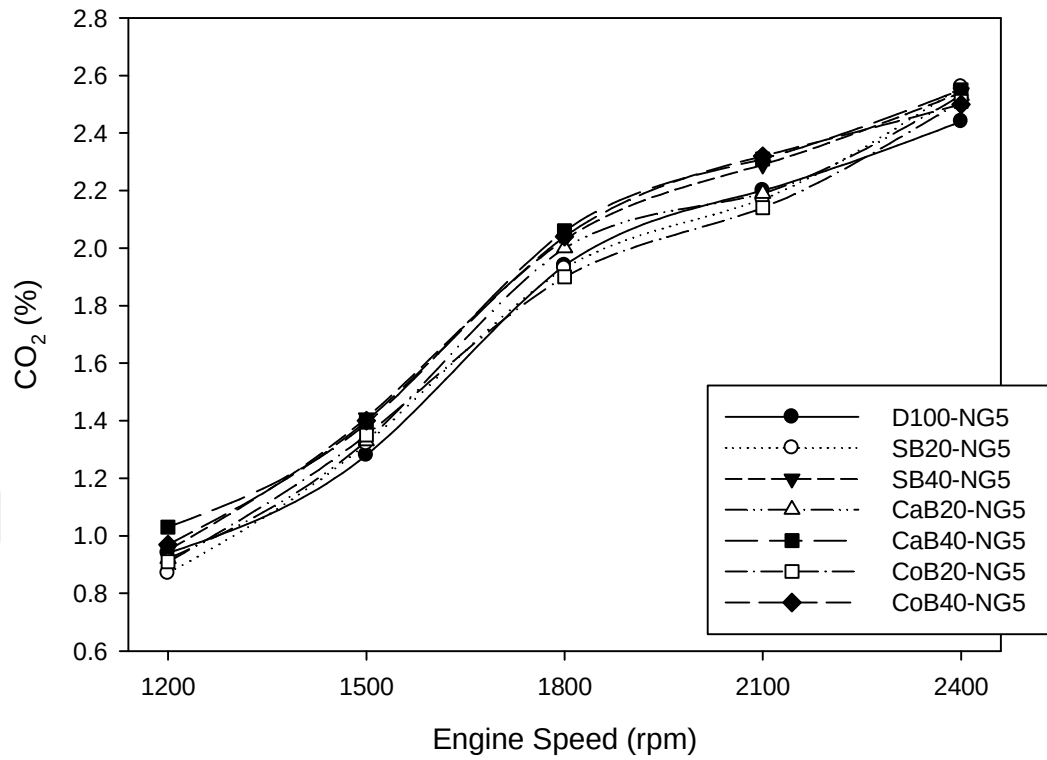
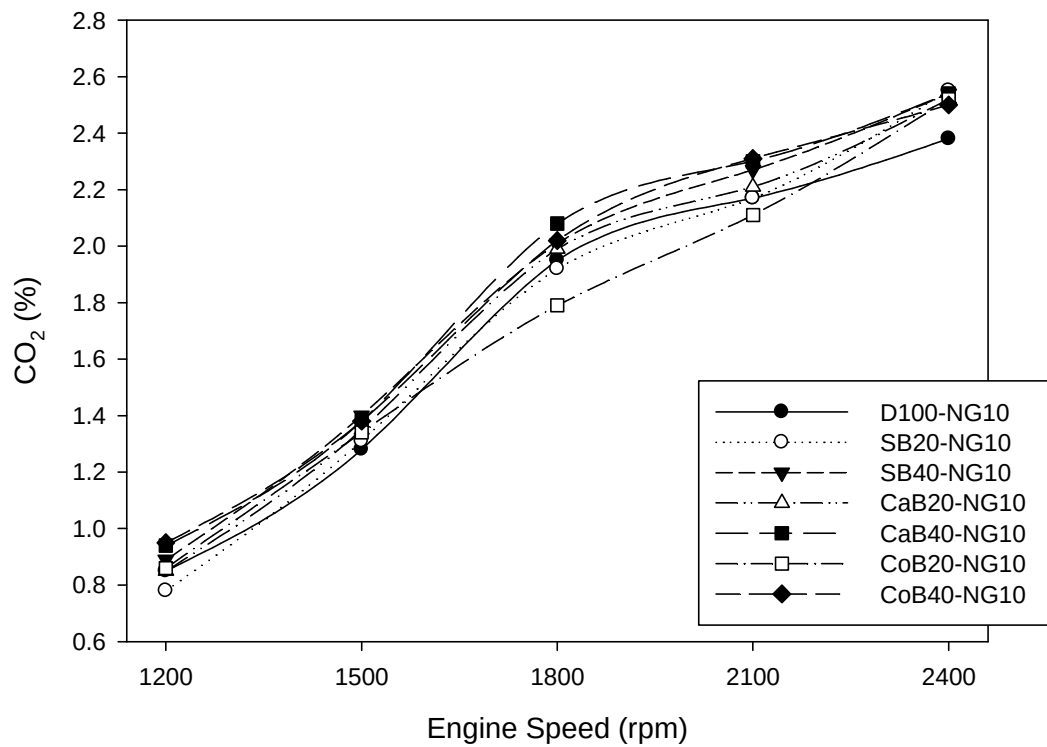


Figure 5.54. CO₂ emission values without NG addition

Figure 5.55. CO₂ emission values with NG5 additionFigure 5.56. CO₂ emission values with NG10 addition

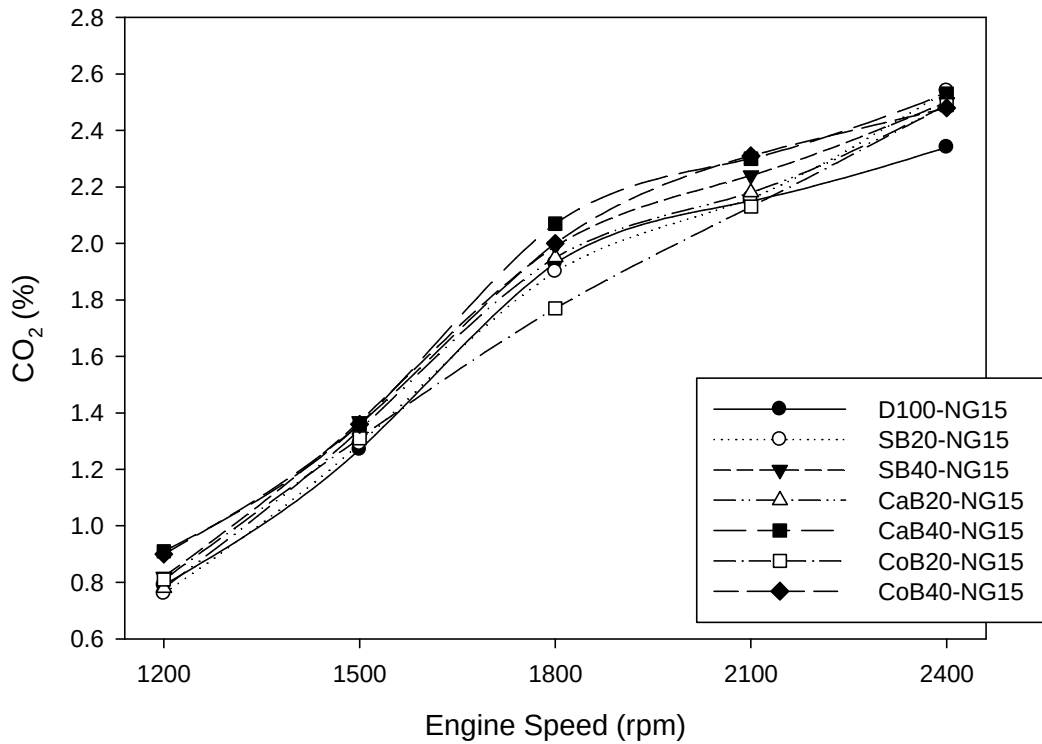
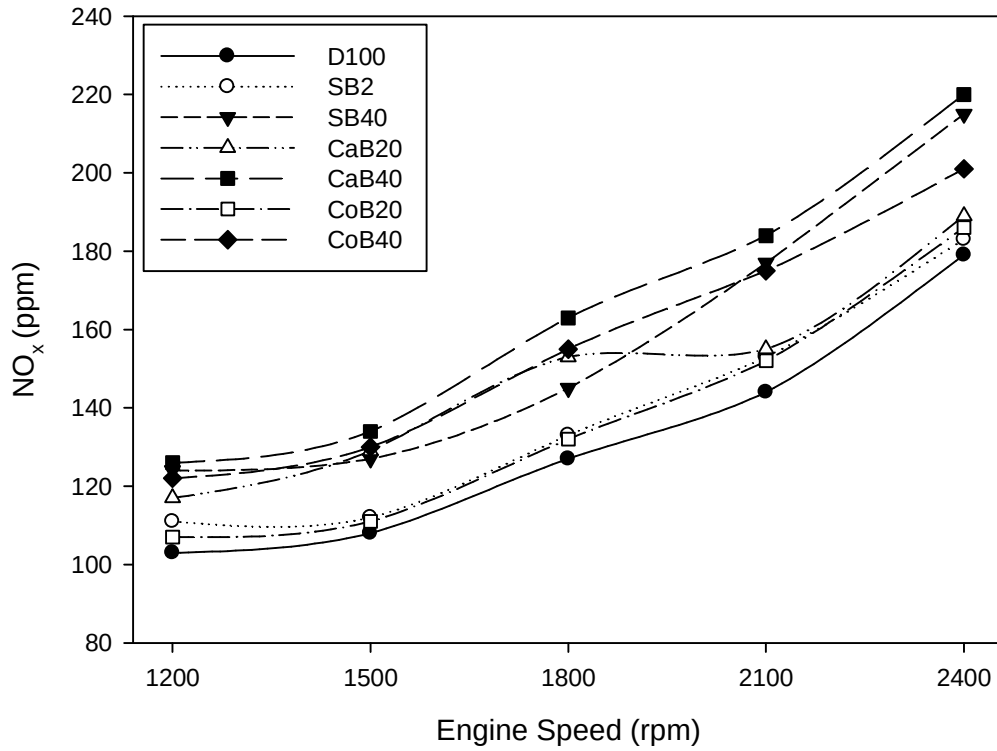
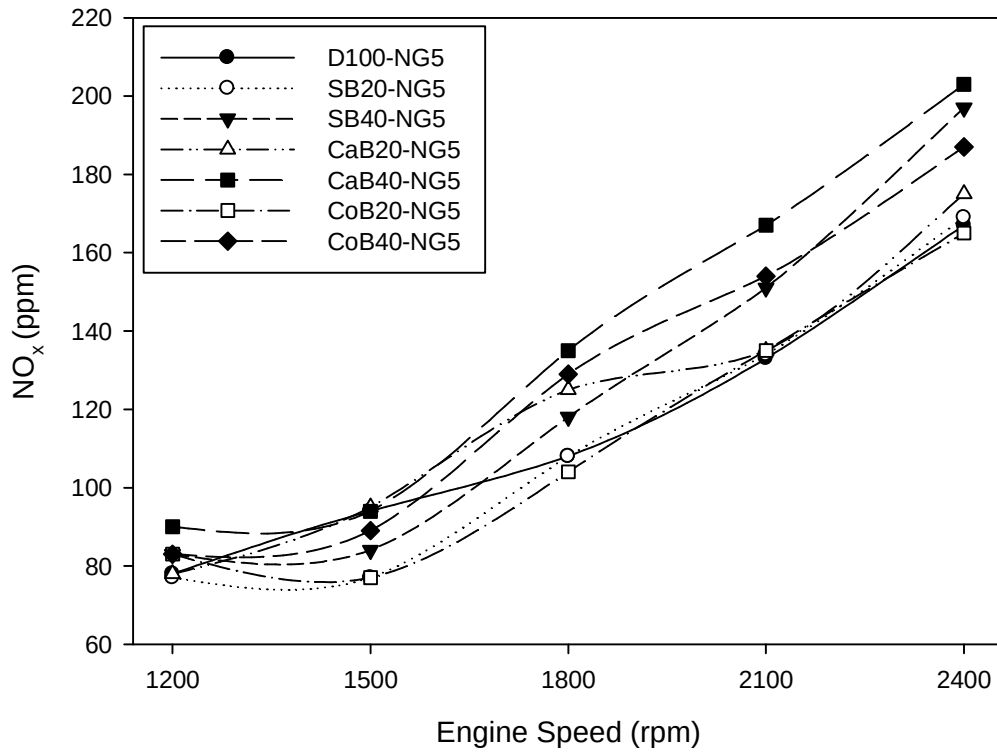
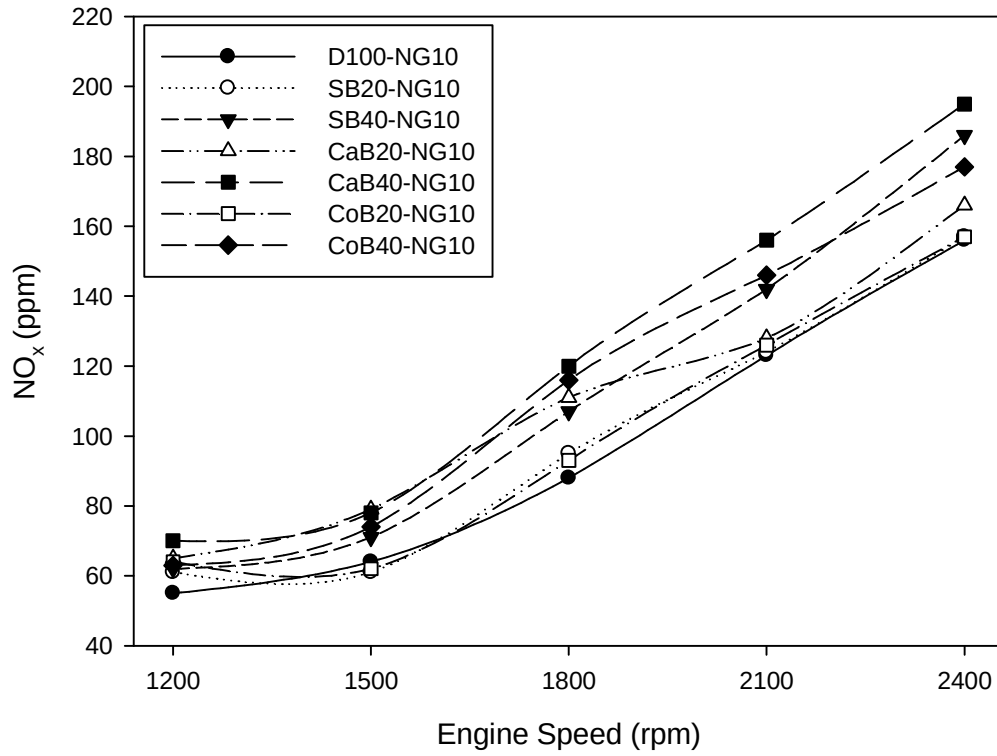
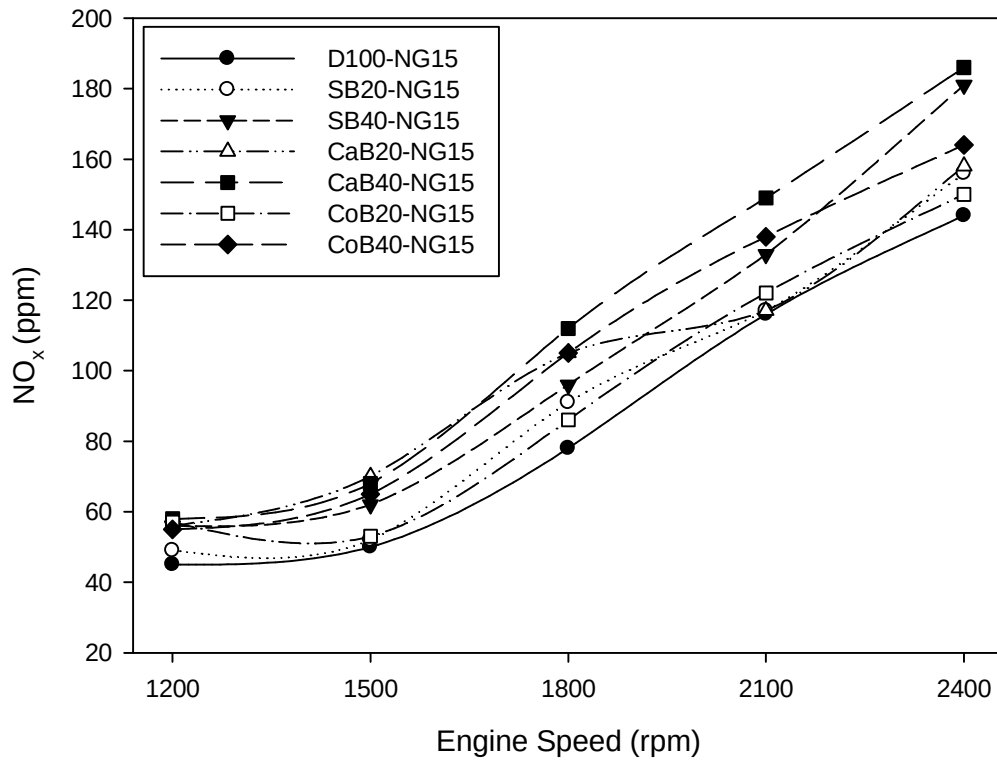


Figure 5.57. CO₂ emission values with NG15 addition

NO_x emissions

Decrease in NO_x emission is primarily due to cooling effect caused by injection of cold CNG into the cylinder. This leads to decrease in peak temperature and hence decrease in NO_x emission (Paul et al., 2014). Therefore, NG5 addition was decreased NO_x emission by 17,4%, NG10 addition increased it by 26,7% and NG15 increased it 32,5% with respect to NG0.

Figure 5.58. NO_x emission values without NG additionFigure 5.59. NO_x emission values with NG5 addition

Figure 5.60. NO_x emission values with NG10 additionFigure 5.61. NO_x emission values with NG15 addition

5.2.2.3. Hydrogen Gas

During the experiments, test engine was fuelled with seven different fuels. These are pure low sulphur diesel (D100), 80% diesel, 20% sunflower biodiesel (SB20), 60% diesel, 40% sunflower biodiesel (SB40), 80% diesel, 20% canola biodiesel (CaB20), 60% diesel, 40% canola biodiesel (CaB40), 80% diesel, 20% corn biodiesel (CoB20), 60% diesel, 40% corn biodiesel (CoB40) by volume and each of them was tested with three different hydrogen flow rate (H0, H3, and H6) at five different engine speed (1200 rpm, 1500 rpm, 1800 rpm, 2100 rpm, and 2400 rpm) with no load condition in order to eliminate the effect of dynamometer loading mechanism.

5.2.2.3.(1). Vibration

Vibration data of the engine was gathered for 10 seconds long for each experiment from the engine block and the sampling frequency was choose as 51,2 kHz.

Time and frequency spectrum at x- y- and z- axes of experiment engine was shown in figures 5.62, 5.63, and 5.64. The figures illustrated the test results of CaB40-H0, CaB40-H3, CaB40-H6 at 2100 rpm.

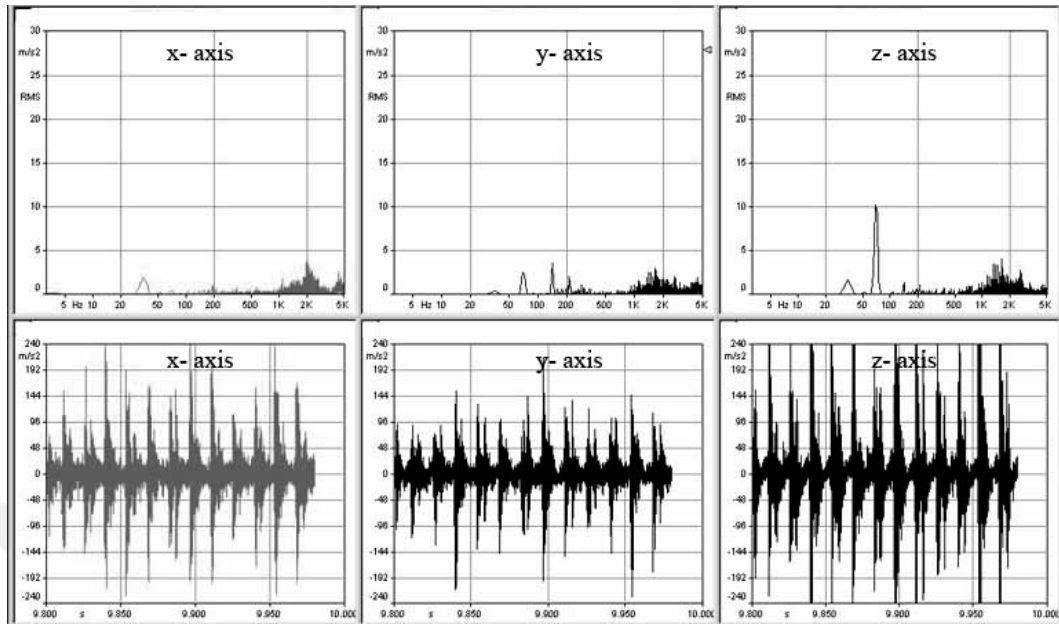


Figure 5.62. Time and frequency spectrum of the engine (CaB40-H0 at 2100 rpm)

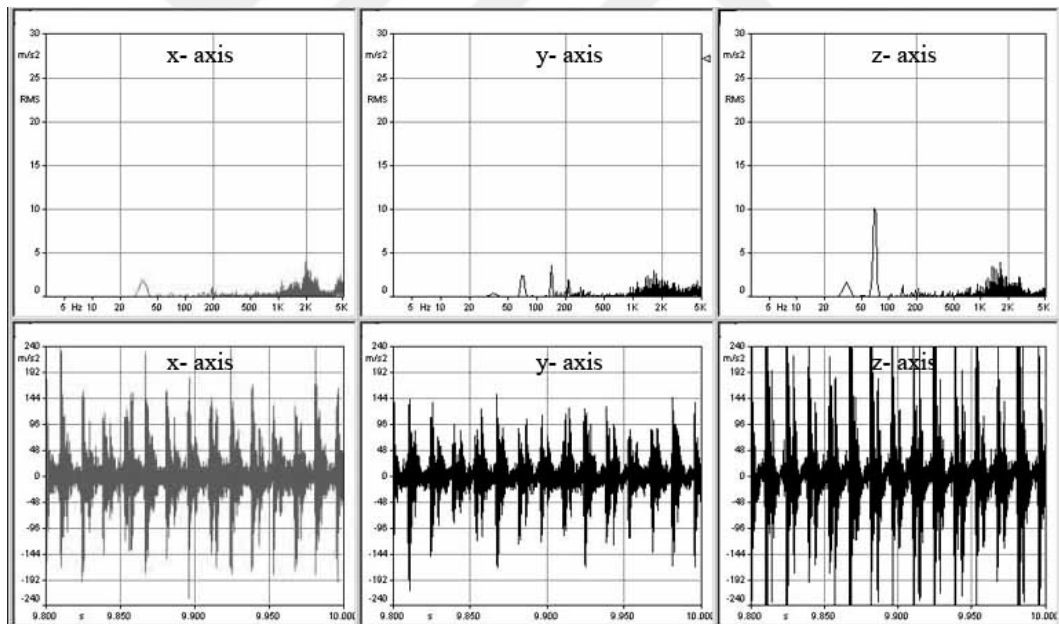


Figure 5.63. Time and frequency spectrum of the engine (CaB40-H3 at 2100 rpm)

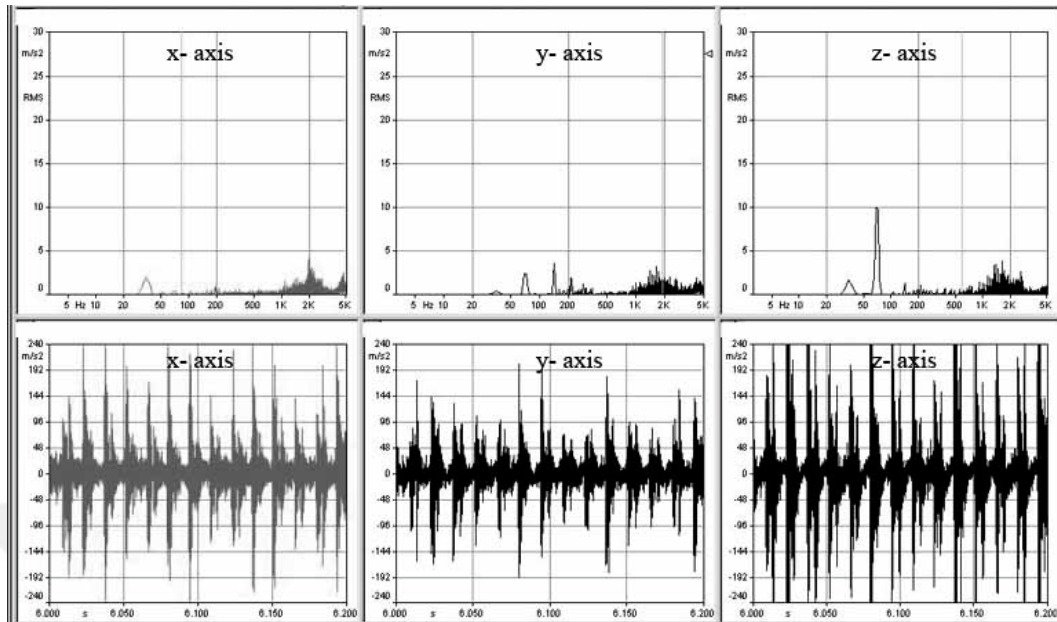


Figure 5.64. Time and frequency spectrum of the engine (CaB40-H6 at 2100 rpm)

Hydrogen addition was decreased engine vibration when the engine was fuelled with each test fuels. Vibration acceleration was decreased by 1,44% and 3,52% with D100; 2,2% and 3,7% with SB20; 0,86% and 1,94% with SB40; 1,53% and 2,59% with CaB20; 0,32% and 1,36% with CaB40; 1,08% and 2,92% with CoB20; 1,44% and 2,76% with CoB40 by adding H3 and H6 into the intake air. The reason of vibration decrement with biodiesel and H₂ gas may due to ignition delay and variation in peak pressure rise rate (How et al., 2014);

The comparison of test results were presented in figure 5.65, 5.66, 5.67, 5.68, and 5.69 at the engine speeds of 1200 rpm, 1500 rpm, 1800 rpm, 2100 rpm, and 2400 rpm, respectively.

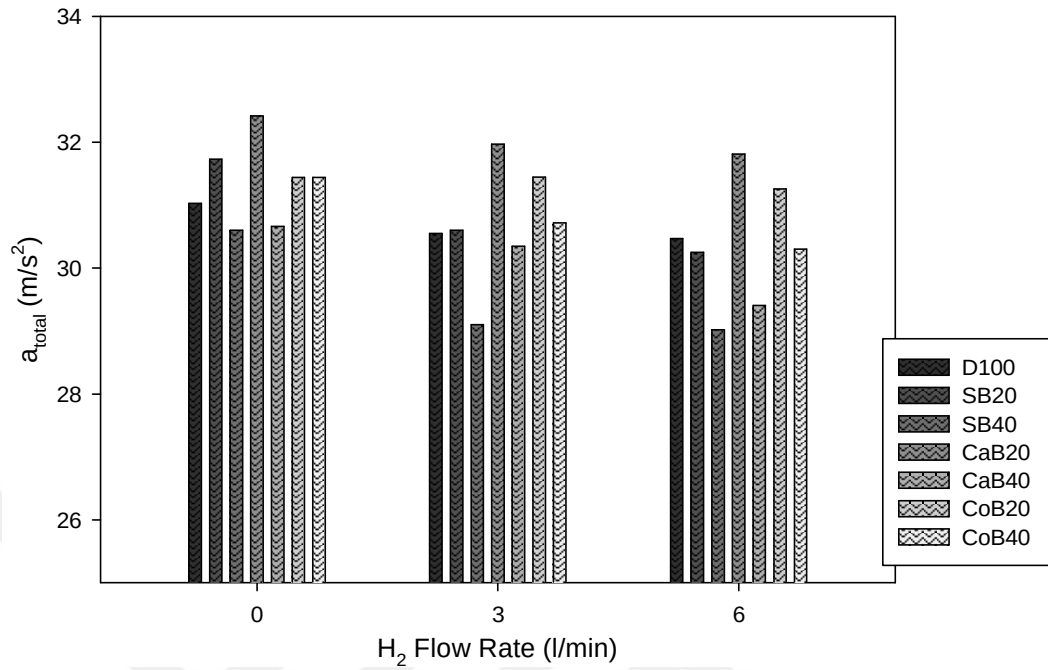


Figure 5.65. a_{total} versus engine speed when the engine fuelled with biodiesels and hydrogen at 1200 rpm

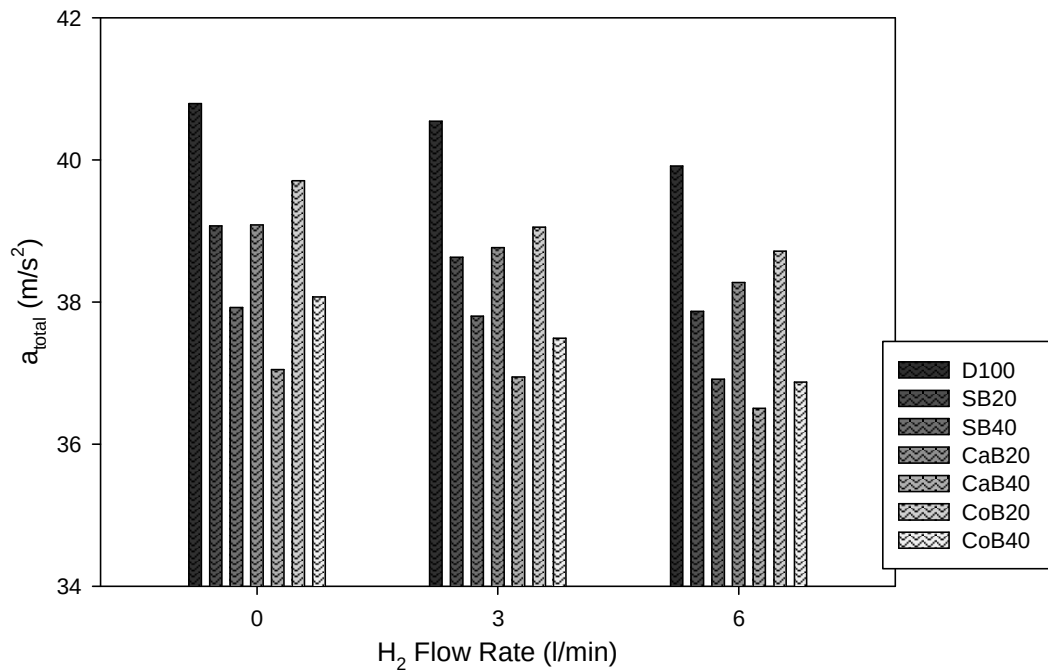


Figure 5.66. a_{total} versus engine speed when the engine fuelled with biodiesels and hydrogen at 1500 rpm

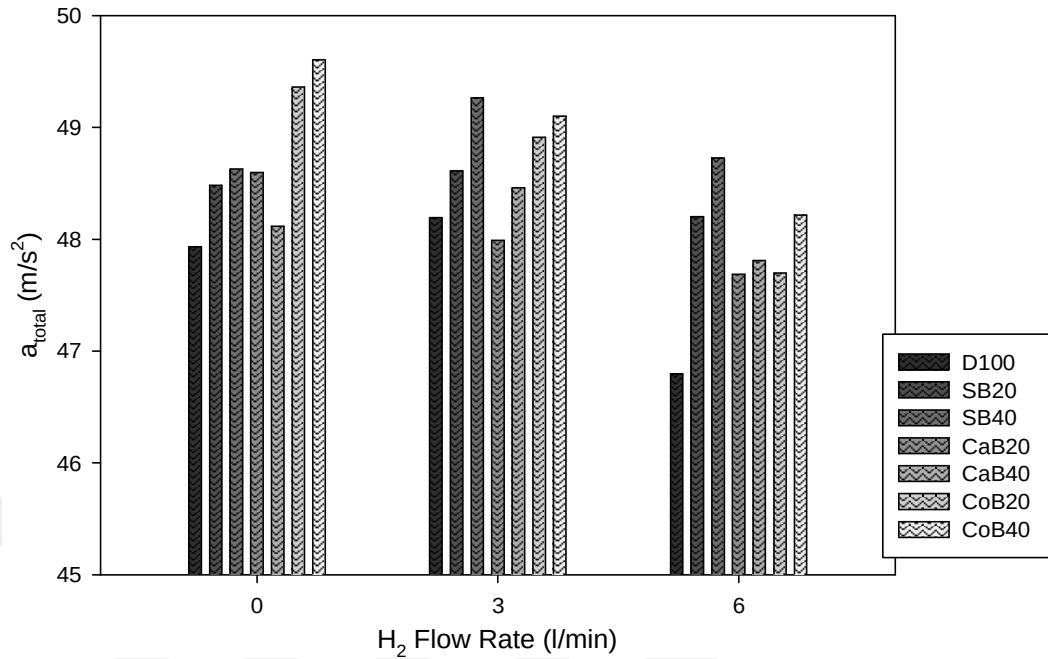


Figure 5.67. a_{total} versus engine speed when the engine fuelled with biodiesels and hydrogen at 1800 rpm

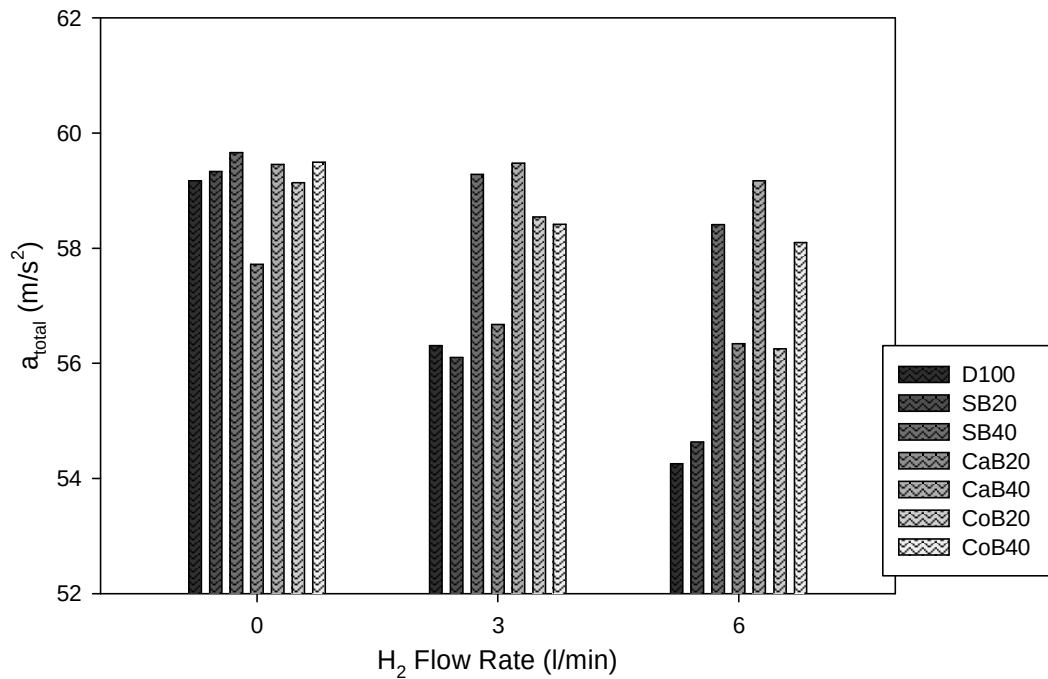


Figure 5.68. a_{total} versus engine speed when the engine fuelled with biodiesels and hydrogen at 2100 rpm

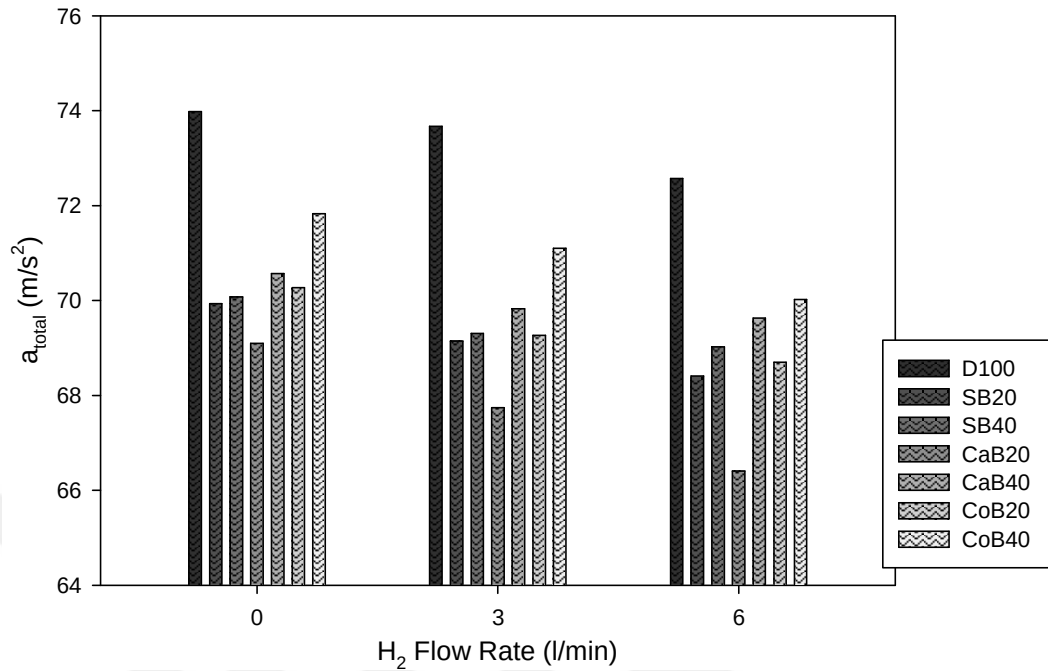


Figure 5.69. a_{total} versus engine speed when the engine fuelled with biodiesels and hydrogen at 2400 rpm

5.2.2.3.(2). Sound Pressure Level

SPL of the engine also decreased with H₂ addition. This expected phenomenon is maybe the result of decrement of engine vibration. Averagely H₂ addition into intake air decreased the SPL slightly (0,1 dB(A) for both H3 and H6 additions that of H0). The results were presented in following figures.

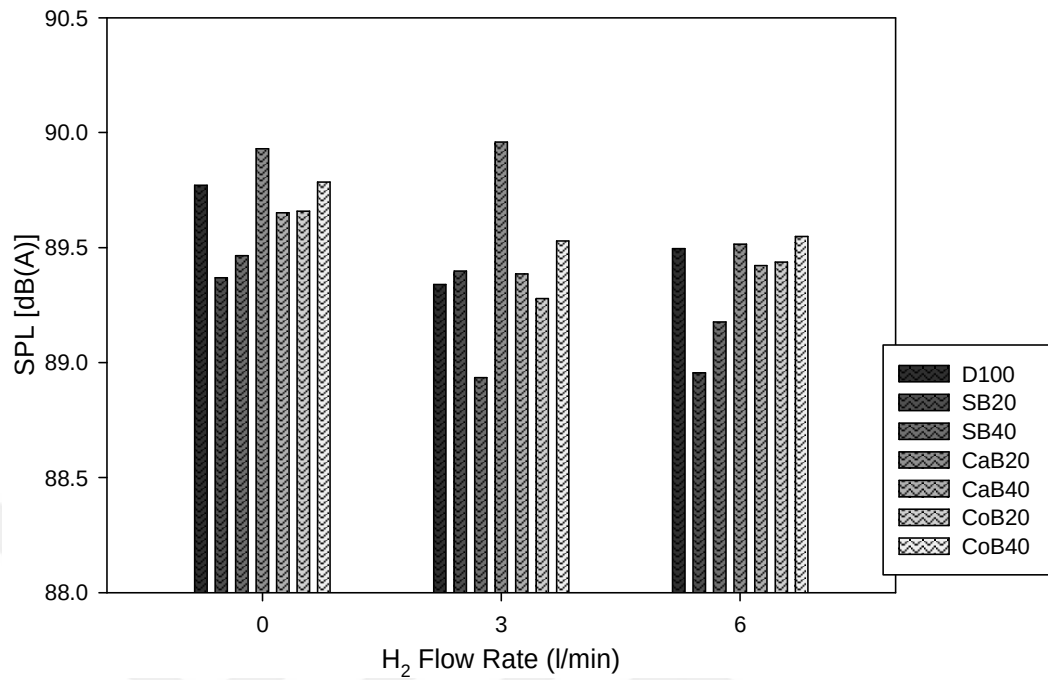


Figure 5.70. SPL versus engine speed when the engine fuelled with biodiesels and hydrogen at 1200 rpm

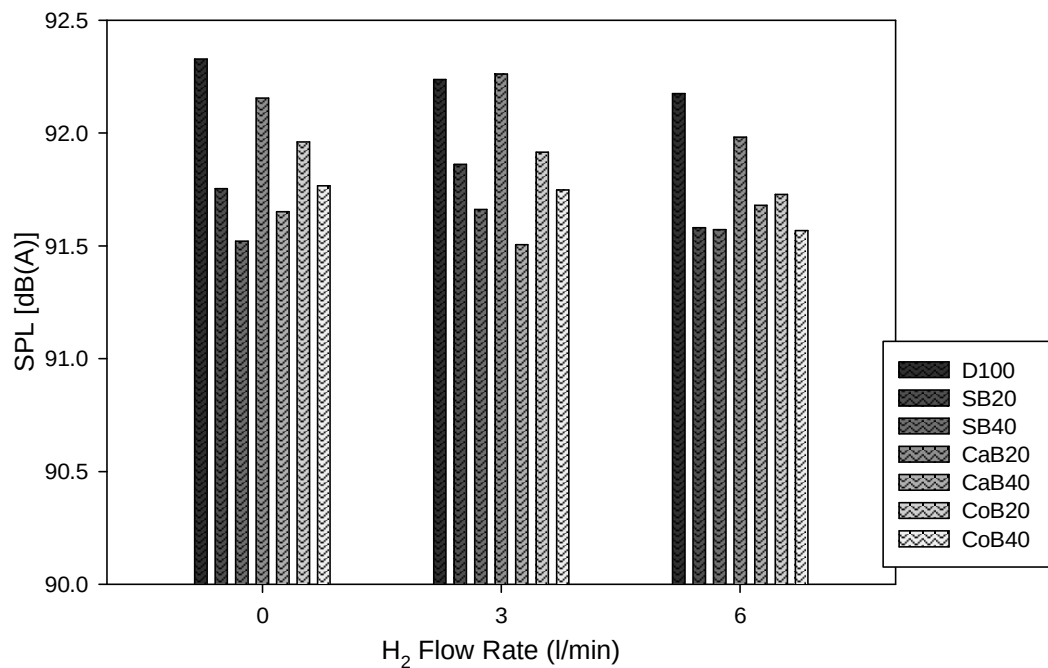


Figure 5.71. SPL versus engine speed when the engine fuelled with biodiesels and hydrogen at 1500 rpm

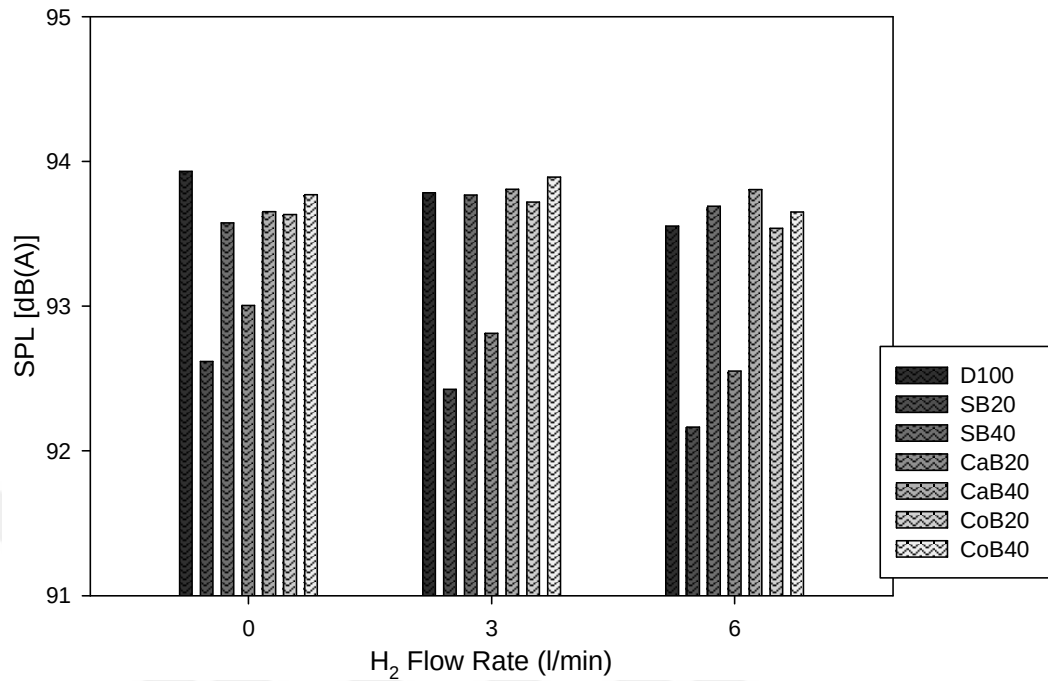


Figure 5.72. SPL versus engine speed when the engine fuelled with biodiesels and hydrogen at 1800 rpm

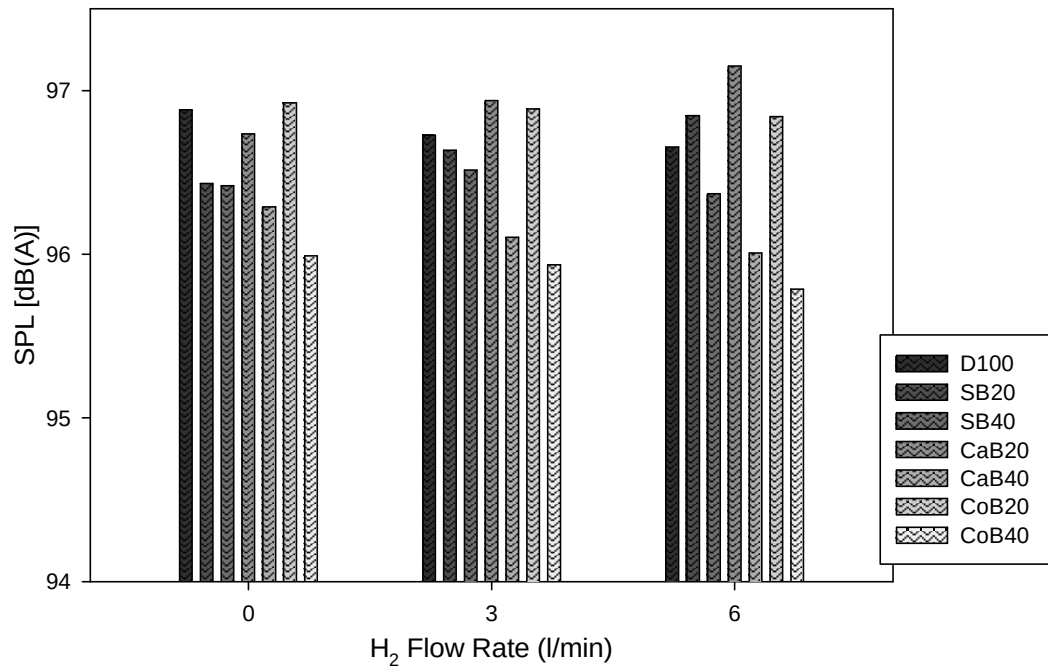


Figure 5.73. SPL versus engine speed when the engine fuelled with biodiesels and hydrogen at 2100 rpm

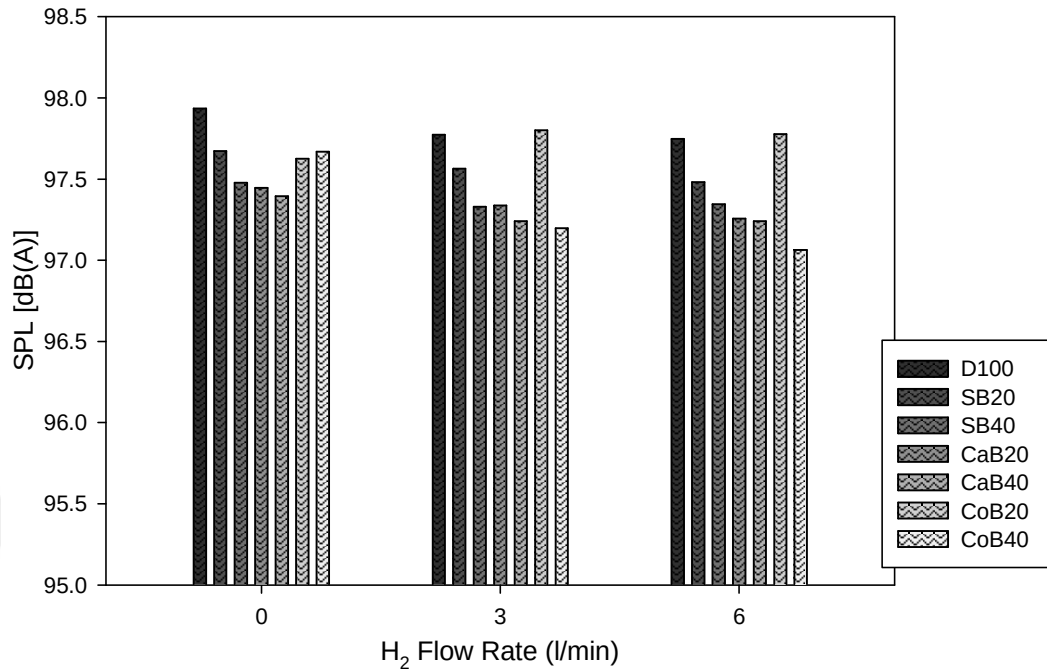


Figure 5.74. SPL versus engine speed when the engine fuelled with biodiesels and hydrogen at 2400 rpm

5.2.2.3.(3). Emission

CO emissions

Incomplete combustion is the main reason of CO emission formation (Li et al., 2015). In figures 5.75, 5.76, and 5.77 illustrate the CO values. CO formation decreased 7,7%, and 11,4%, for addition of H3 and H6, that of H0. More complete combustion enhanced with biodiesel usage thus, CO emission was decreased as mentioned before; furthermore addition of H₂ were further decreased the values because the gas is absence of carbon (Yılmaz, et al., 2010).

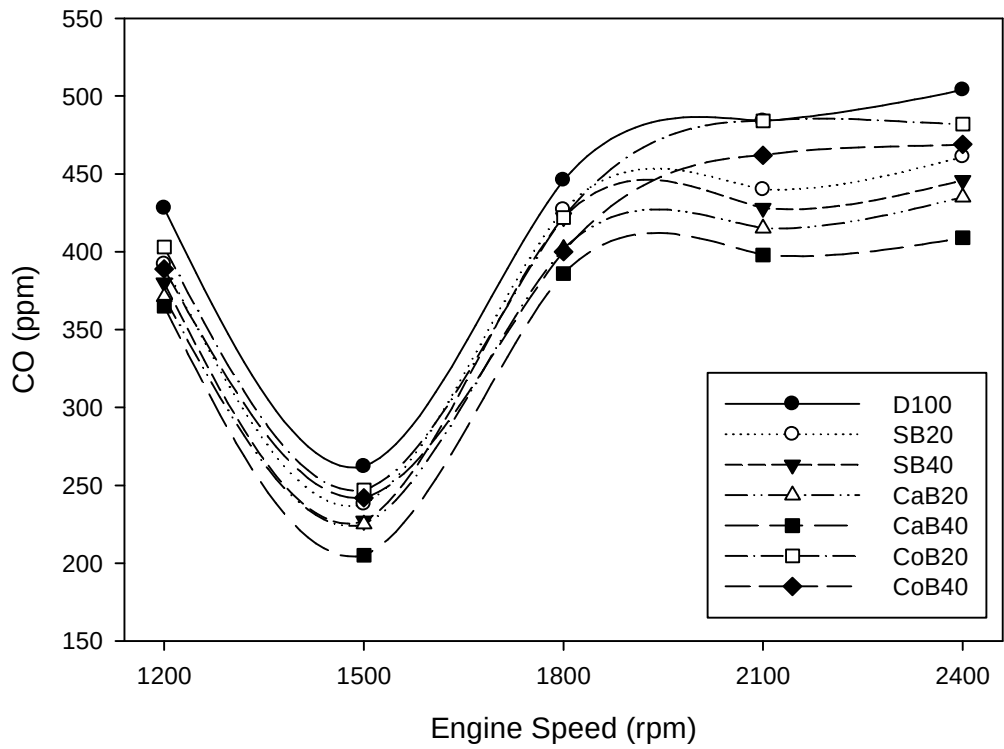


Figure 5.75. CO emission values without hydrogen addition

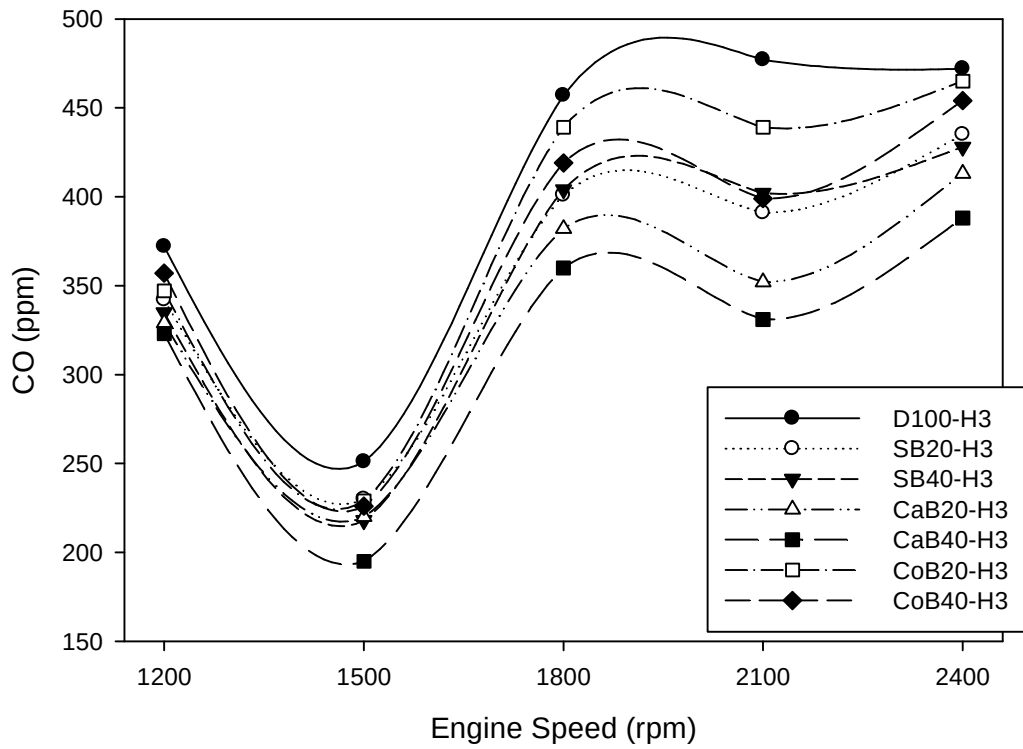


Figure 5.76. CO emission values with H3

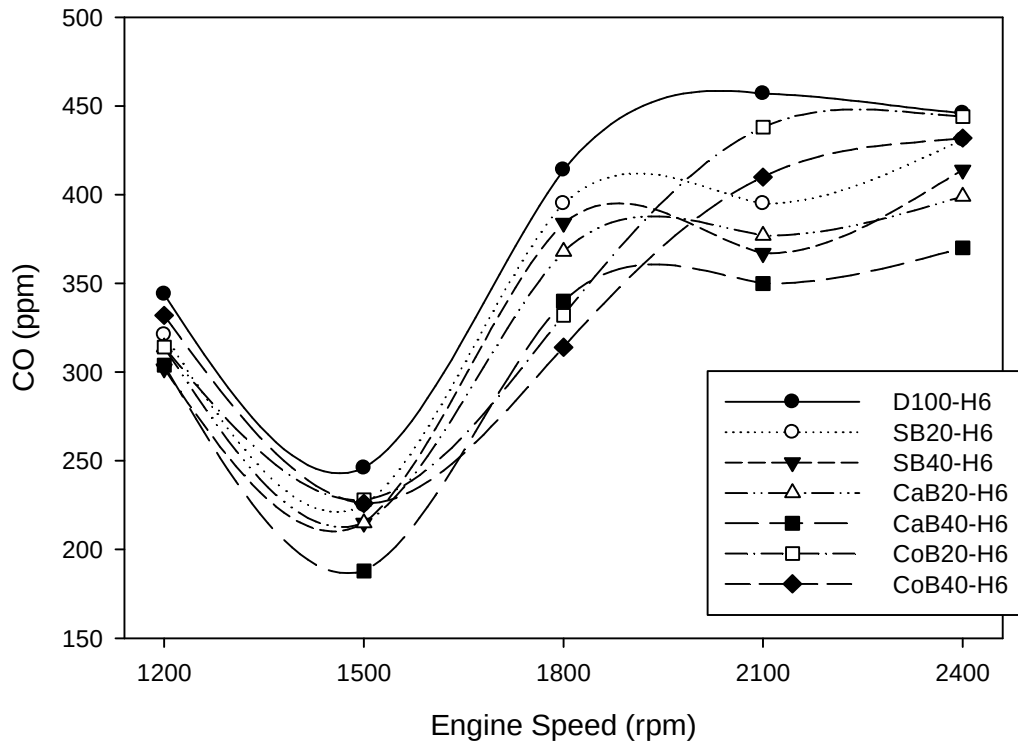
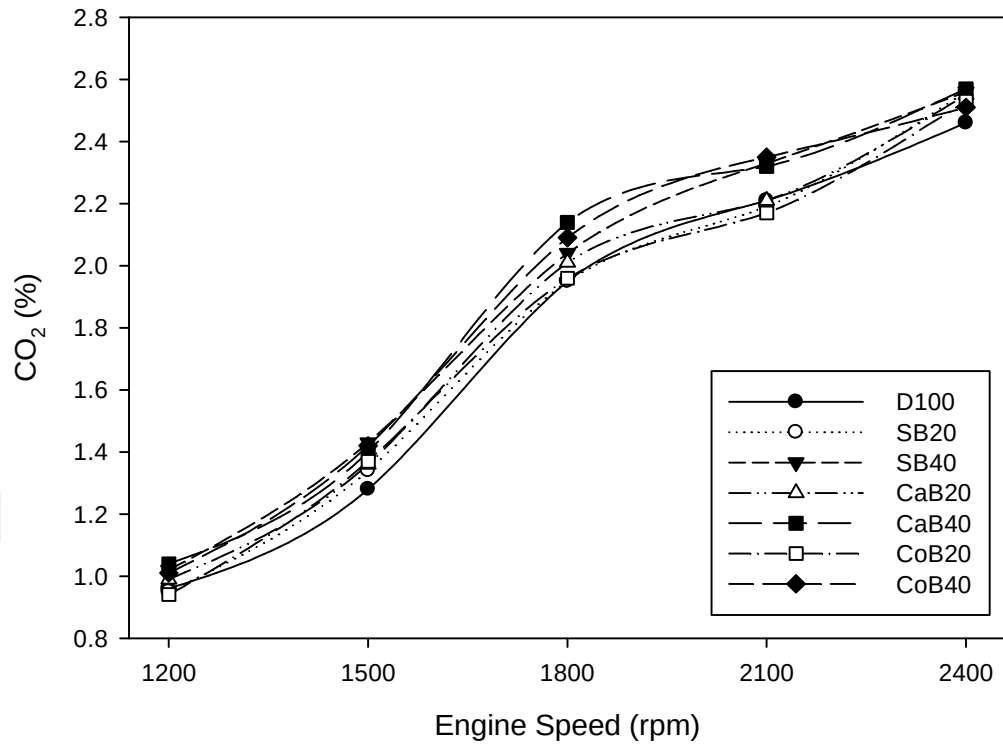
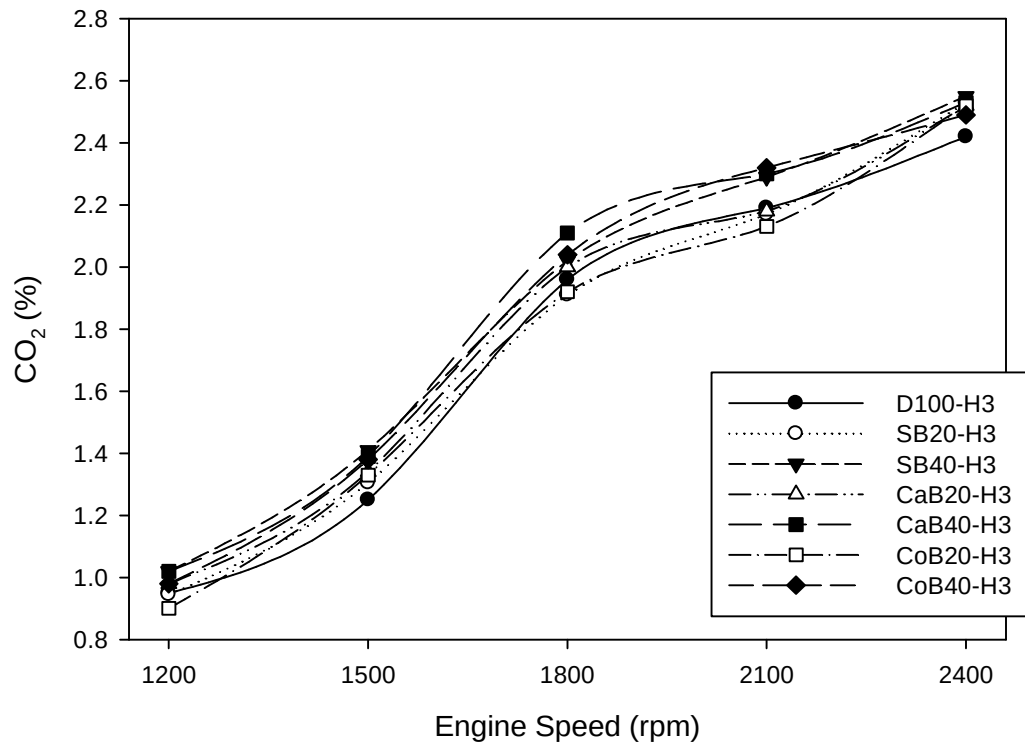


Figure 5.77. CO emission values with H6

CO₂ emissions

In figure 7.78, 7.79, and 7.80 CO₂ emission values were shown with H0, H3, and H6 addition. As it can be seen in figures, CO₂ emission decreased by hydrogen enrichment due to the absence of carbon in H₂, and this reduces the overall amount of carbon atoms available for carbon dioxide (or monoxide) formation (Jhang et al., 2016). According to results, compared to H0 results, H3 addition decreased CO₂ emission by 1,4% whereas H6 decreased it 2,2%.

Figure 5.78. CO₂ emission values without hydrogen additionFigure 5.79. CO₂ emission values with H₃

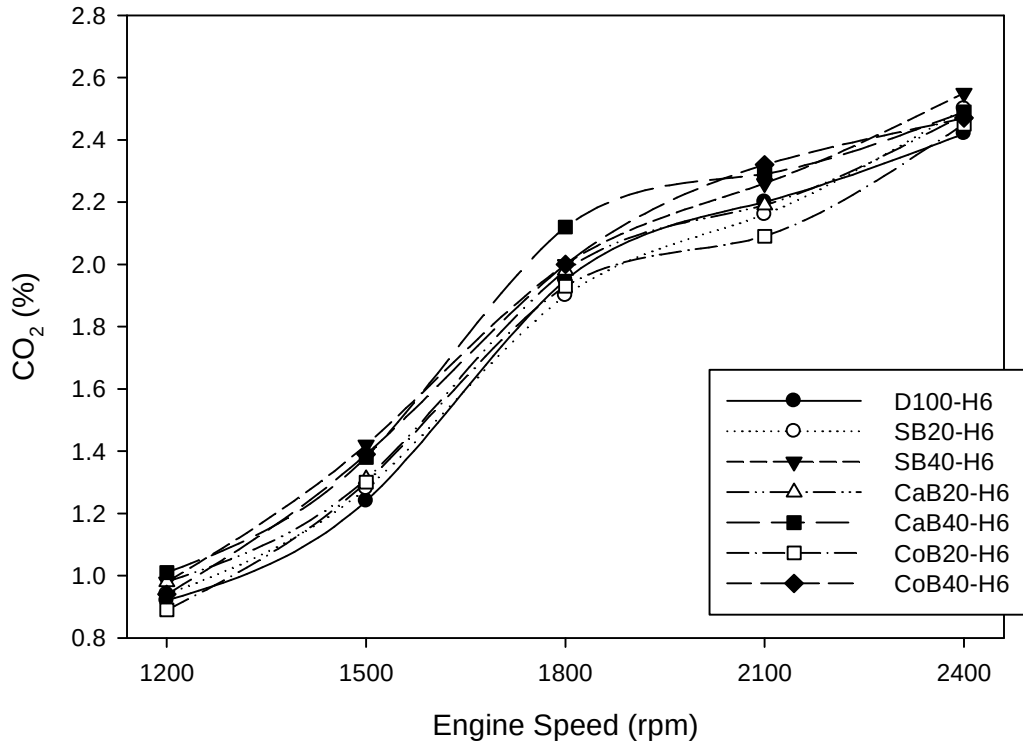
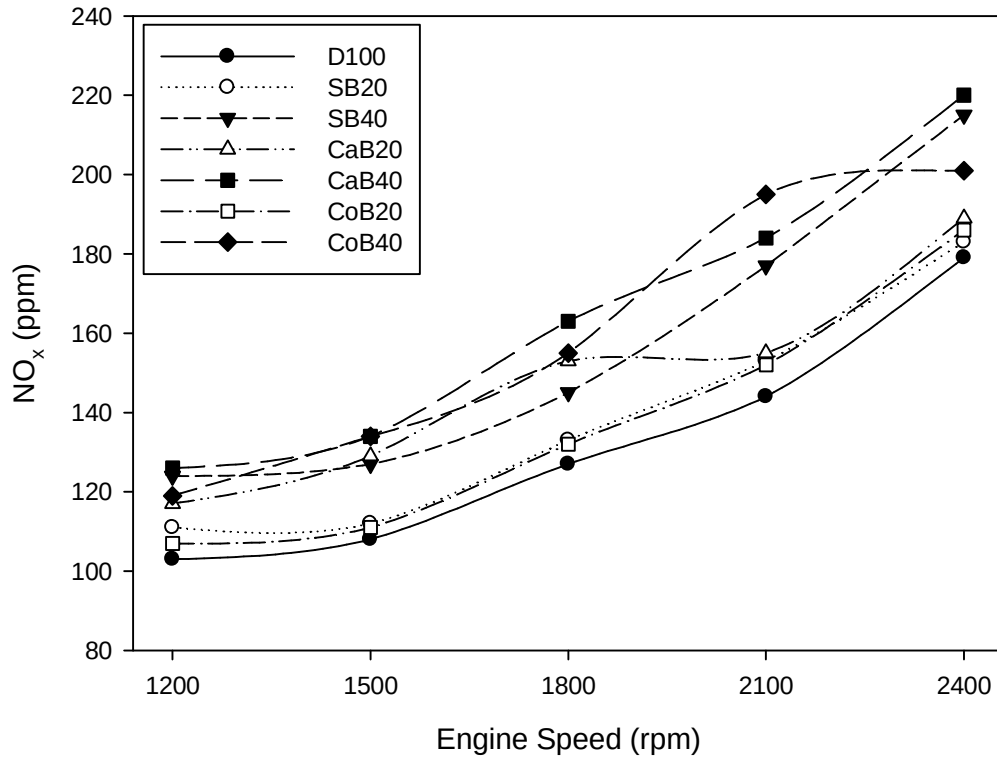
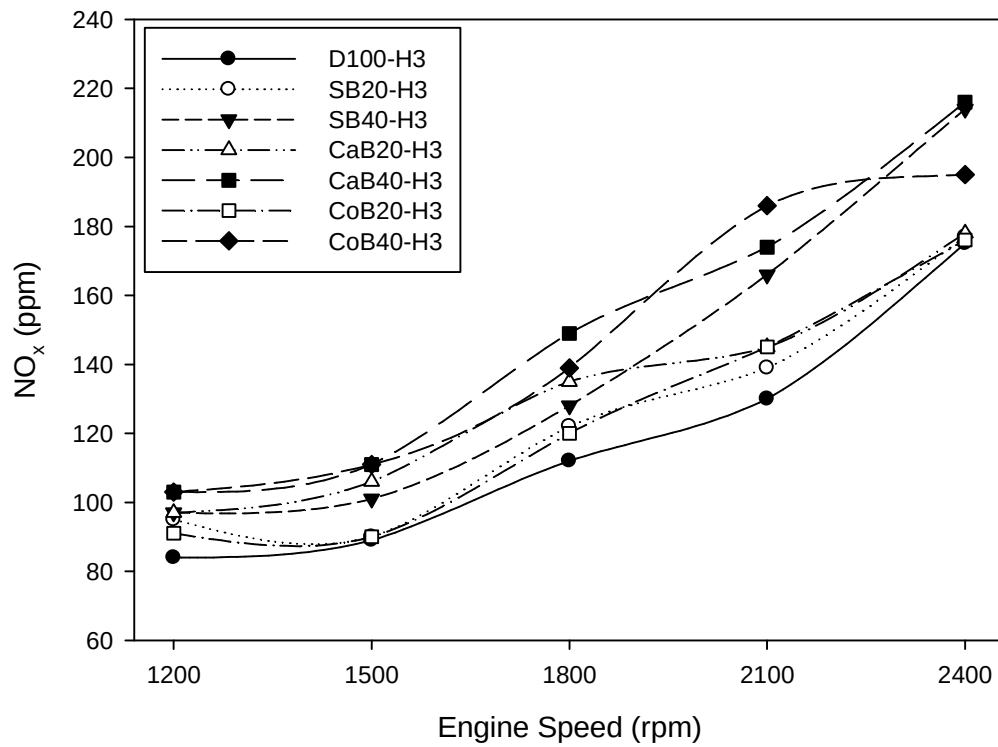
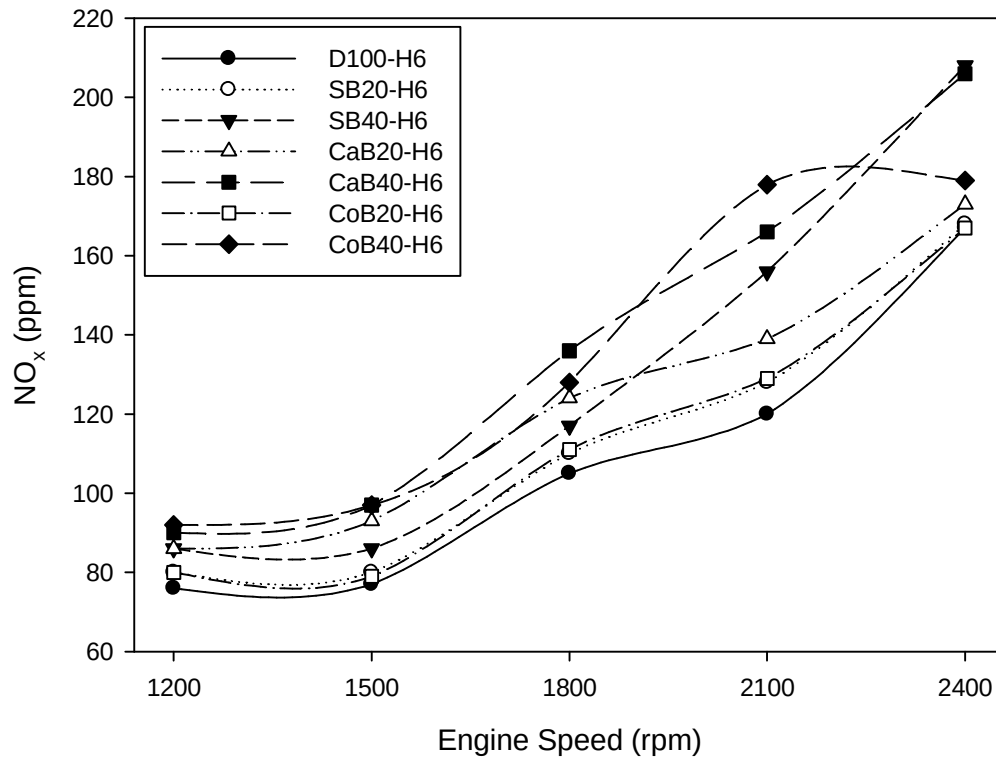


Figure 5.80. CO₂ emission values with H6

NO_x emissions

NO_x emission values for test fuels with H₂ addition were shown in figure 17, 18, and 19. NO_x formation is affected by higher combustion and flame temperature (Tüccar et al., 2014b). There is an increase with biodiesel usage due to extra oxygen content of biodiesels that caused higher combustion temperature. Even though, this trend was also expected with H₂ addition since hydrogen has higher flame speed propagation than diesel and biodiesels, since the experiments in this study has evaluated without any load, a decreased in NO_x emissions occurred with H₂ addition because of the equivalence ratio at the fuel rich combustion, and this helps in maintaining a lower cylinder temperature, which effectively inhibits the production of NO_x (Deb et al., 2015; Jhang et al., 2016). The increment was measured as 9,9% and 17,1% with H3 and H6 addition respectively.

Figure 5.81. NO_x emission values without hydrogen additionFigure 5.82. NO_x emission values with H3

Figure 5.83. NO_x emission values with H6

5.2.3. Experimental Engine 3

In this test rig Kirloskar Oil Engine-240 diesel engine was used in order to evaluation of noise and vibration measurement with various compression ratio of the engine cylinder. The effect of combustion characteristic on noise and vibration was studied under no load and 60% load conditions. 12:1, 14:1, and 16:1 were selected as compression ratios to evaluate the effect of CR on engine noise and vibration. D100, SB20, SB40, SB60, SB80, SB100, CaB20, CaB40, CaB60, CaB80, CaB100, CoB20, CoB40, CoB60, CoB80, and CoB100 biodiesels were used as fuel during the experiments. The results of them were presented in following sections.

5.2.3.1. Vibration

According to the test results, increase of engine load caused a significant increase in engine vibration acceleration, at all compression ratios. Vibration

acceleration of the engine was also decreased with increasing compression ratio. This trend may be due to the increment of compression ratio cause a reduction in ignition delay time. In-cylinder pressure with a consequent decrease in injection duration enforces the fuel droplets to be better atomised. As a consequence of better atomization, reduced ignition delay, the fine spray immediately ignites such that the bulk of the heat release happens within a short span. Increment of compression ratio from 12:1 to 14:1 increased the engine vibration acceleration as 3,03% and 2,06% and to 16:1 increased it 3,75% and 3,11%, for under no load and 60% load conditions, respectively.

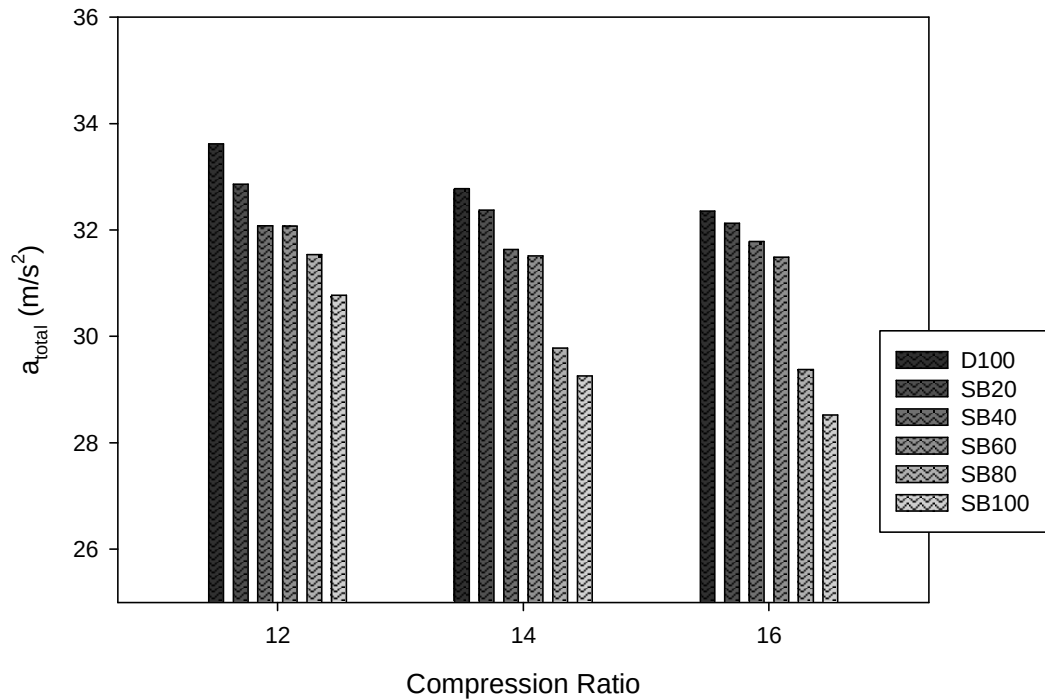


Figure 5.84. a_{total} versus compression ratio under no load condition when the engine fuelled with sunflower biodiesel blends

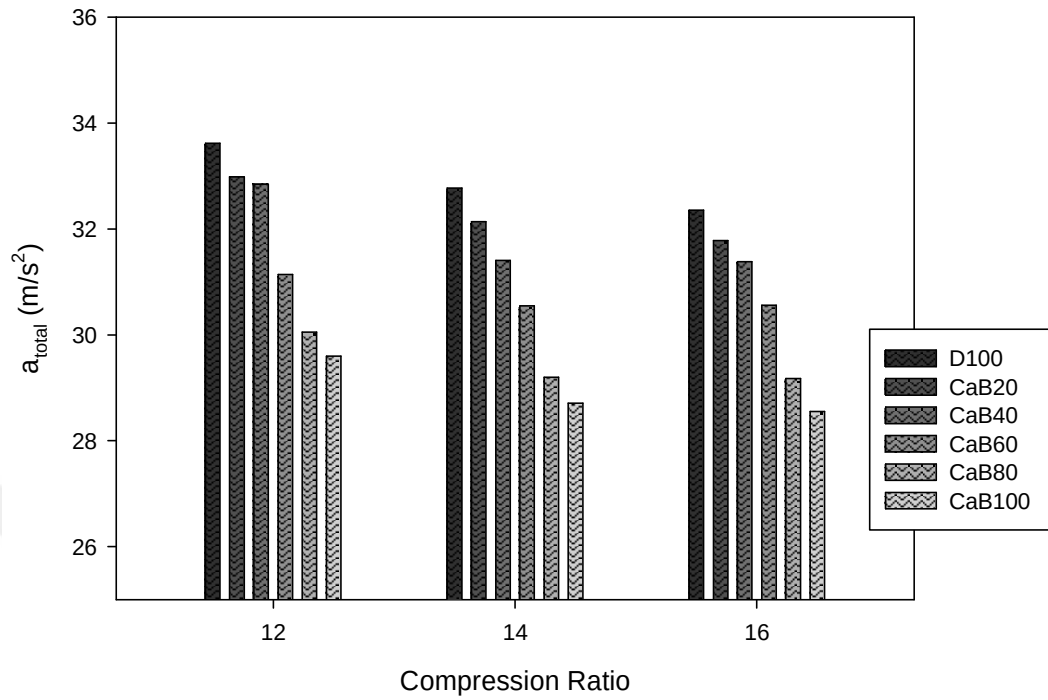


Figure 5.85. a_{total} versus compression ratio under no load condition when the engine fuelled with canola biodiesel blends

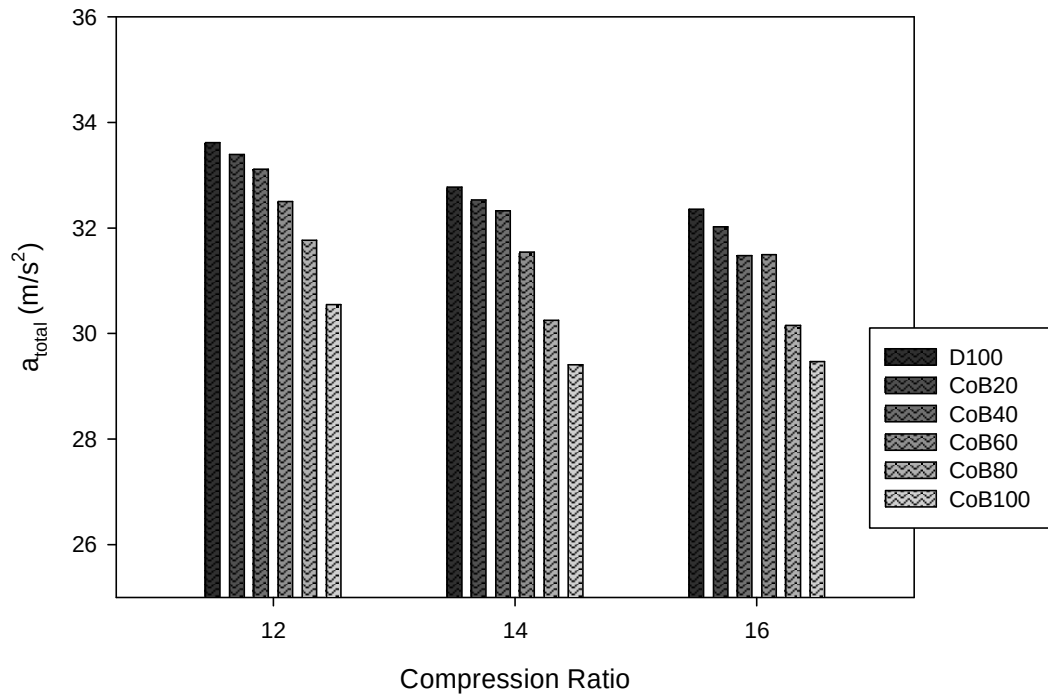


Figure 5.86. a_{total} versus compression ratio under no load condition when the engine fuelled with corn biodiesel blends

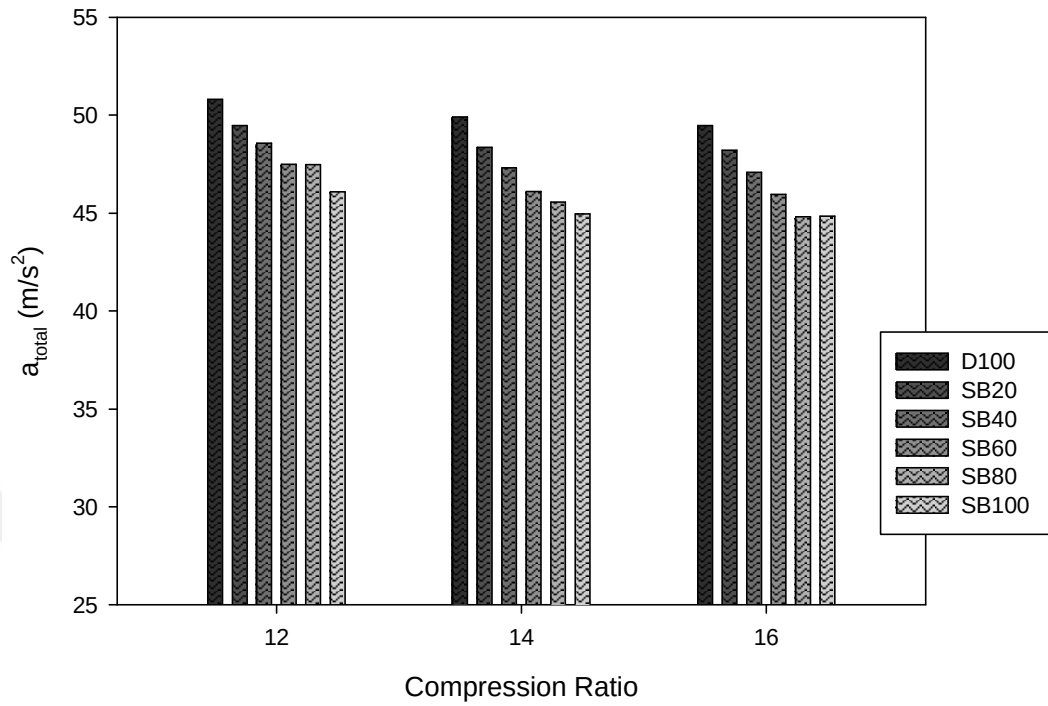


Figure 5.87. a_{total} versus compression ratio under %60 load condition when the engine fuelled with sunflower biodiesel blends

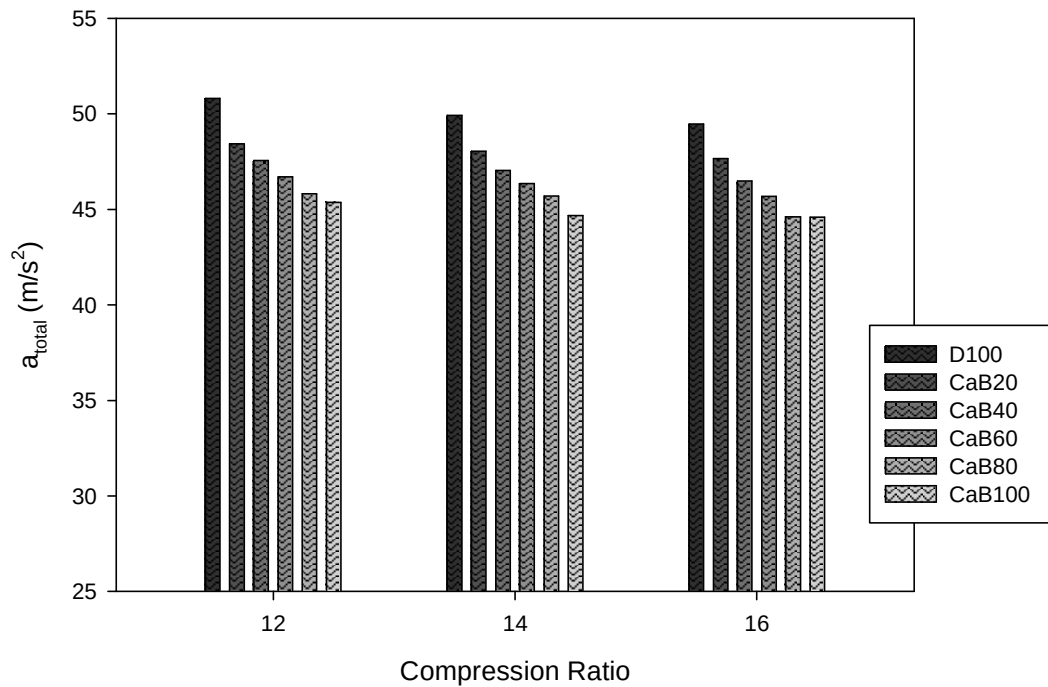


Figure 5.88. a_{total} versus compression ratio under %60 load condition when the engine fuelled with canola biodiesel blends

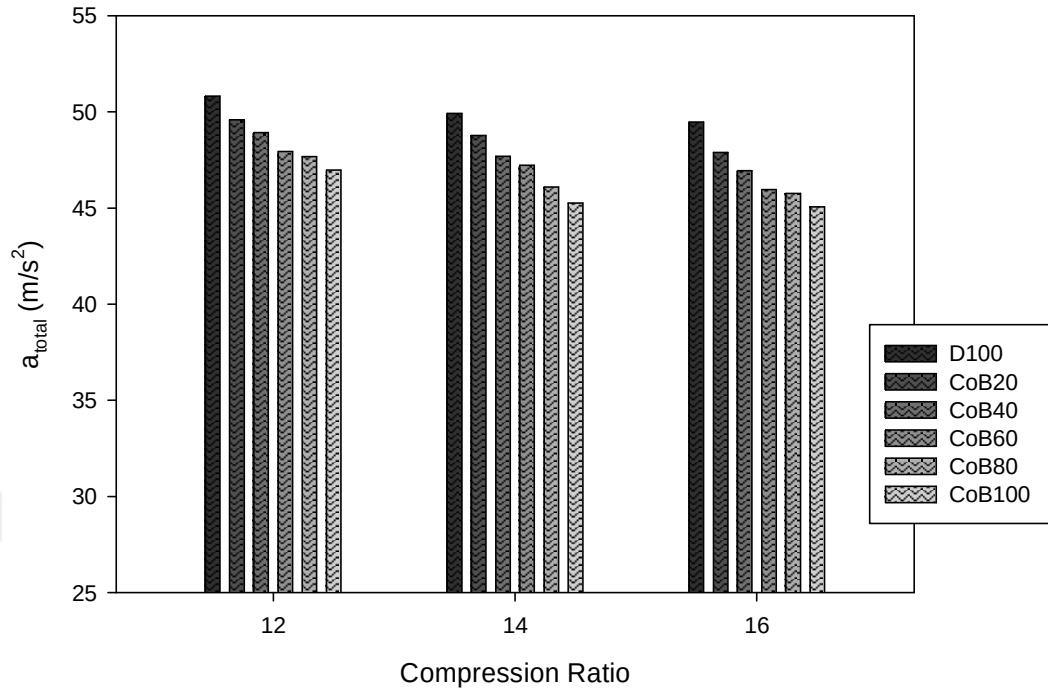


Figure 5.89. a_{total} versus compression ratio under %60 load condition when the engine fuelled with corn biodiesel blends

5.2.3.2. Sound Pressure Level

It observed that, increment of compression ratio usually cause to decrement of SPL level of the engine. Under no load condition, the SPL level was slightly increased (0,01 dB(A)) by changing compression ratio to 14:1 from 12:1, however 0,63 dB(A) decrement were observed when compression ratio was increased to 16:1. 0,13 dB(A) and 0,52 dB(A) improvement was measured under 60% load with 14:1 and 16:1 CR, respectively, that of 12:1 CR. The results were presented in figures 5.90, 5.91, 5.92, 5.93, 5.94, 5.95, and 5.96.

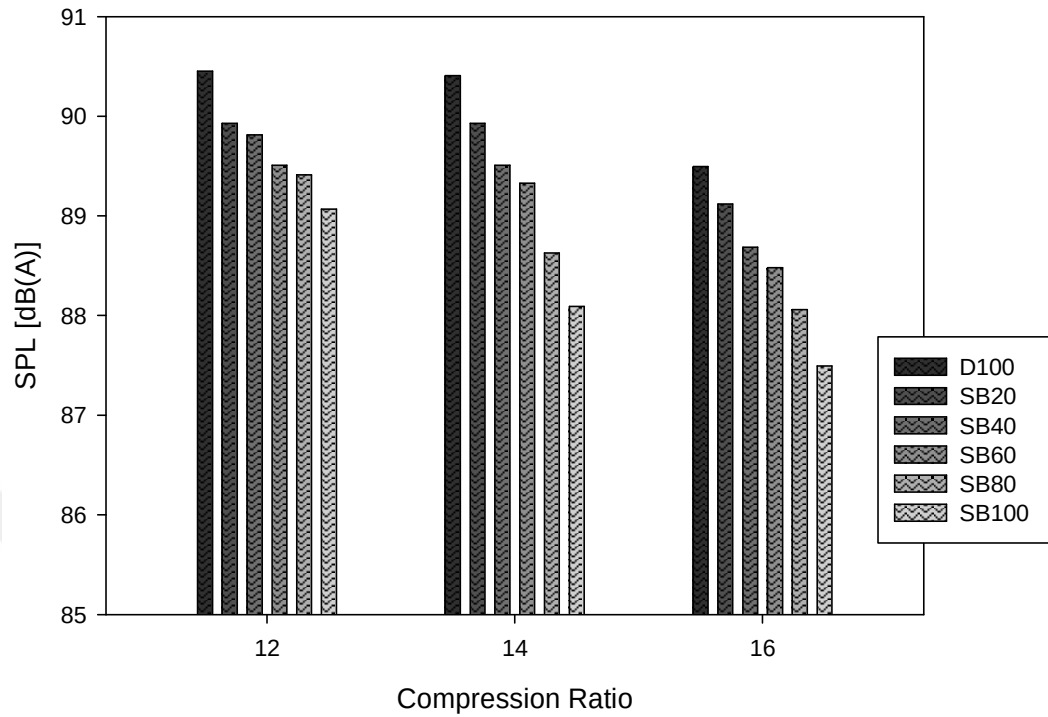


Figure 5.90. SPL versus compression ratio under no load condition when the engine fuelled with sunflower biodiesel blends

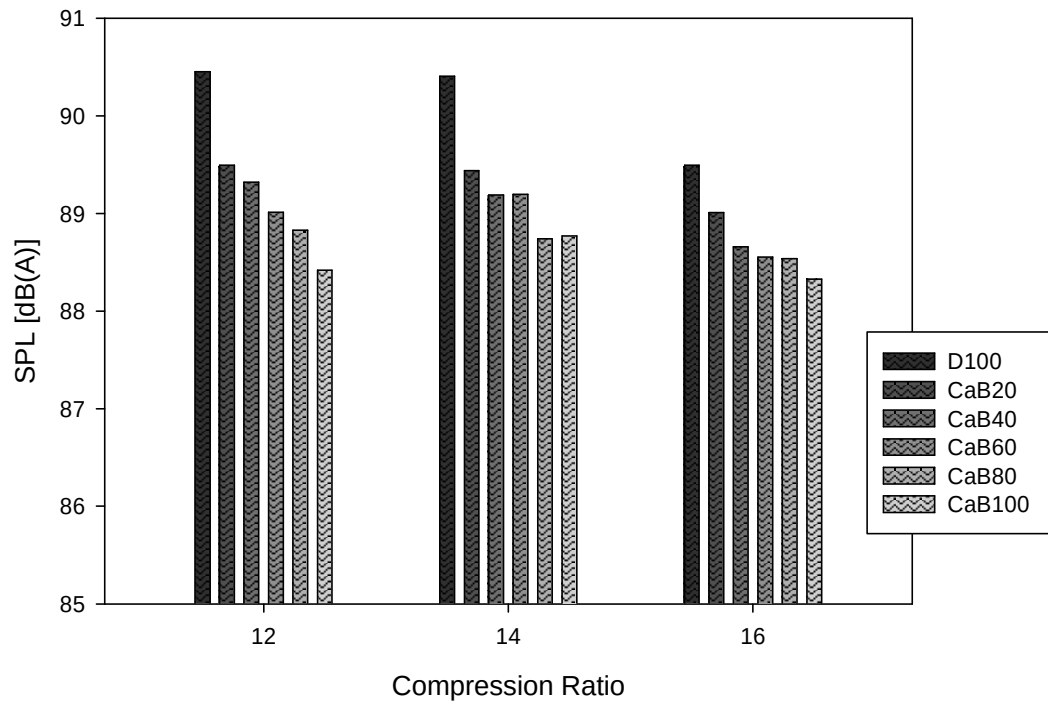


Figure 5.91. SPL versus compression ratio under no load condition when the engine fuelled with canola biodiesel blends

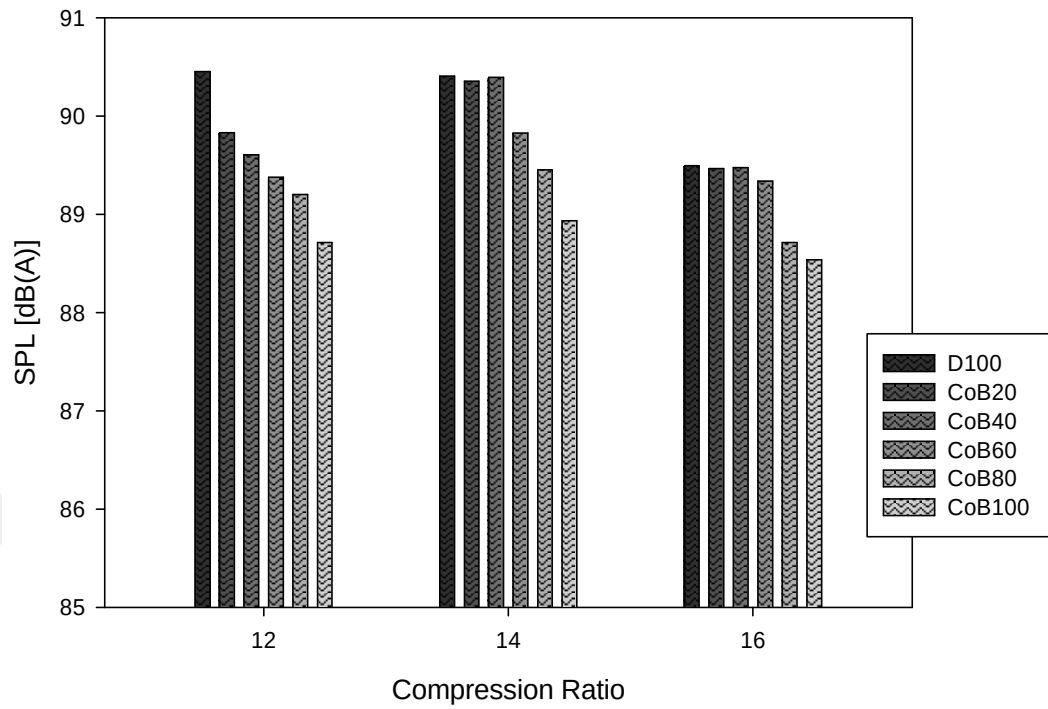


Figure 5.92. SPL versus compression ratio under no load condition when the engine fuelled with corn biodiesel blends

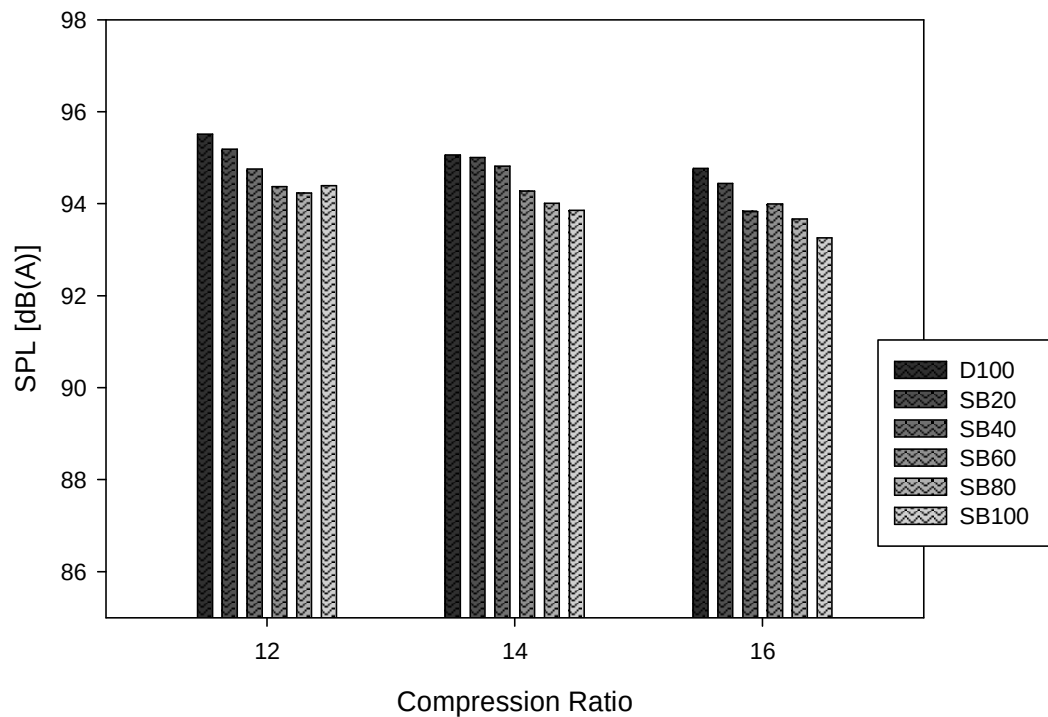


Figure 5.93. SPL versus compression ratio under 60% load condition when the engine fuelled with sunflower biodiesel blends

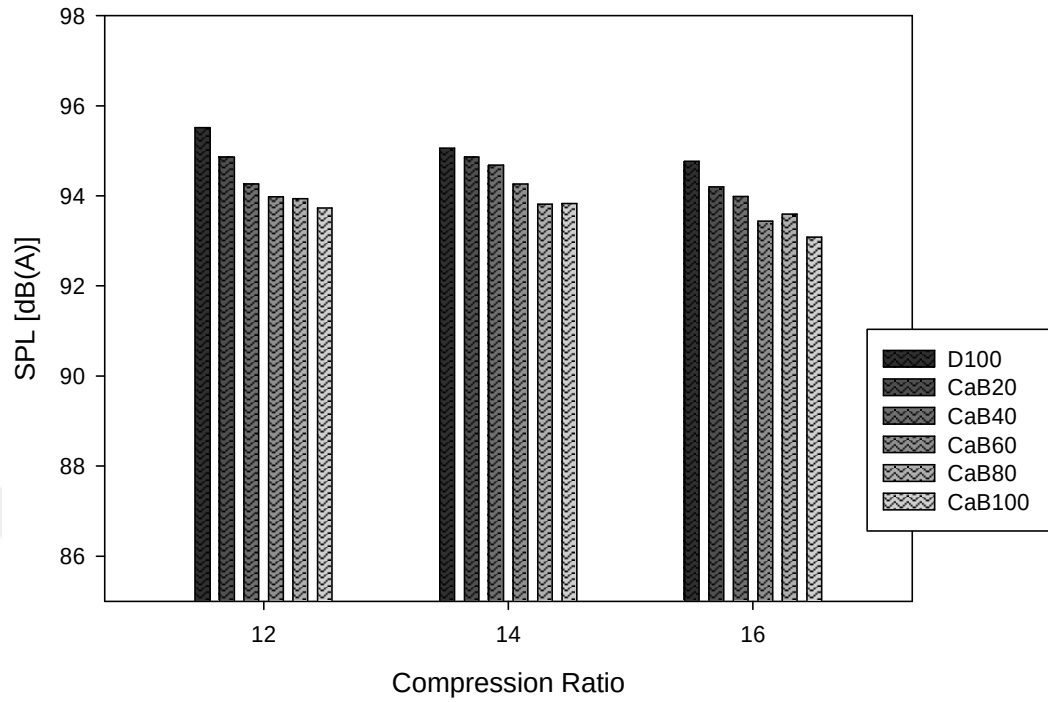


Figure 5.94. SPL versus compression ratio under 60% load condition when the engine fuelled with canola biodiesel blends

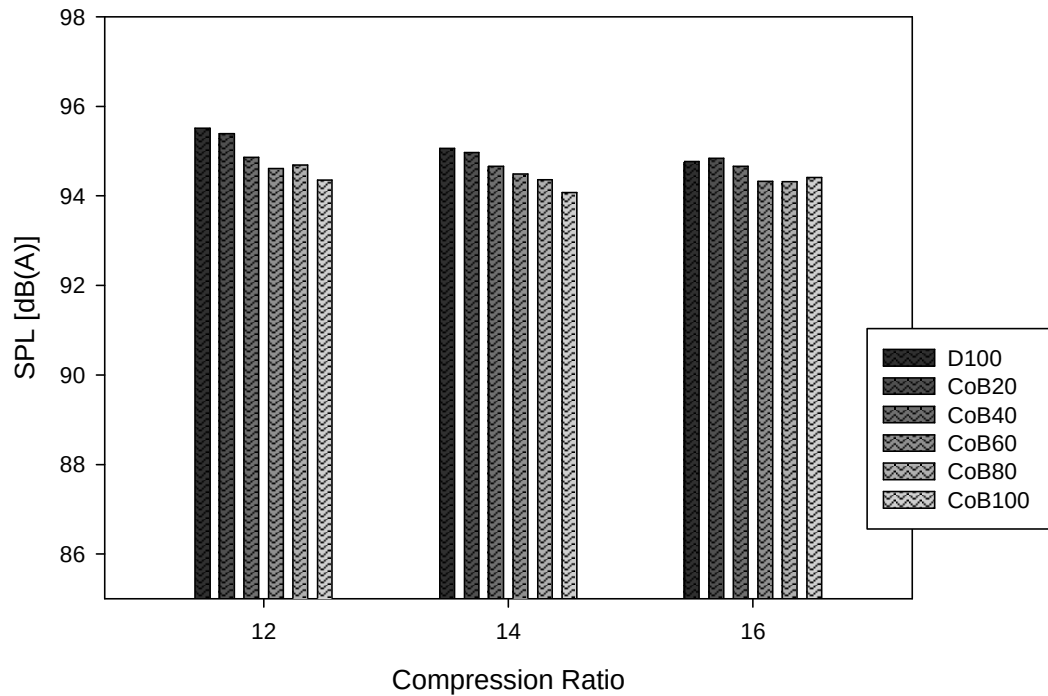


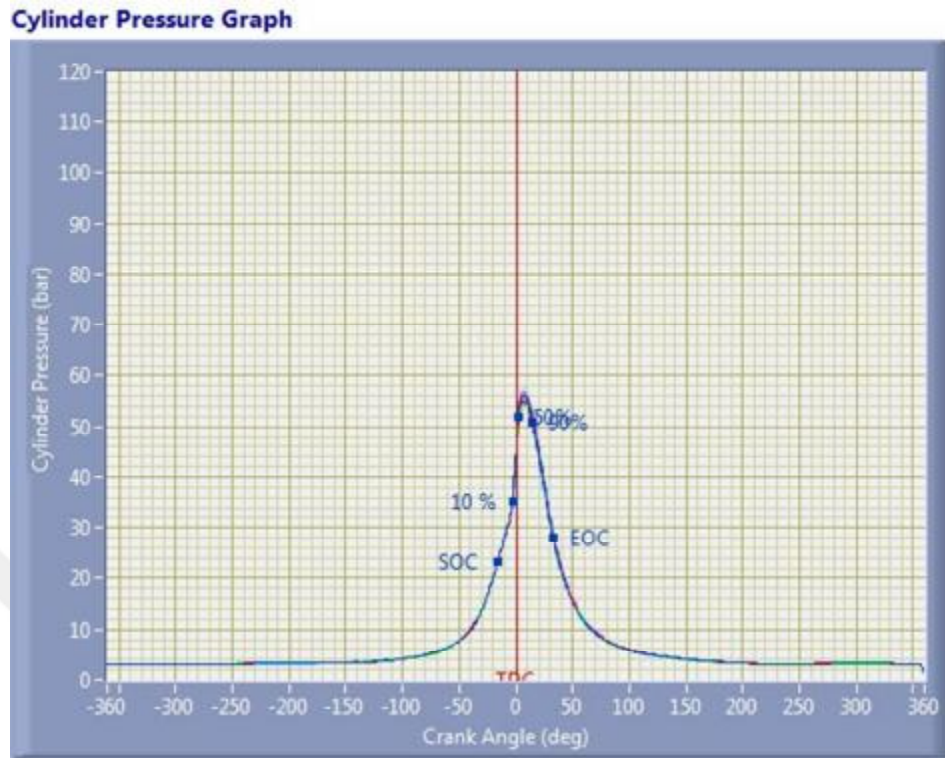
Figure 5.95. SPL versus compression ratio under 60% load condition when the engine fuelled with corn biodiesel blends

5.2.3.3. Combustion Characteristic

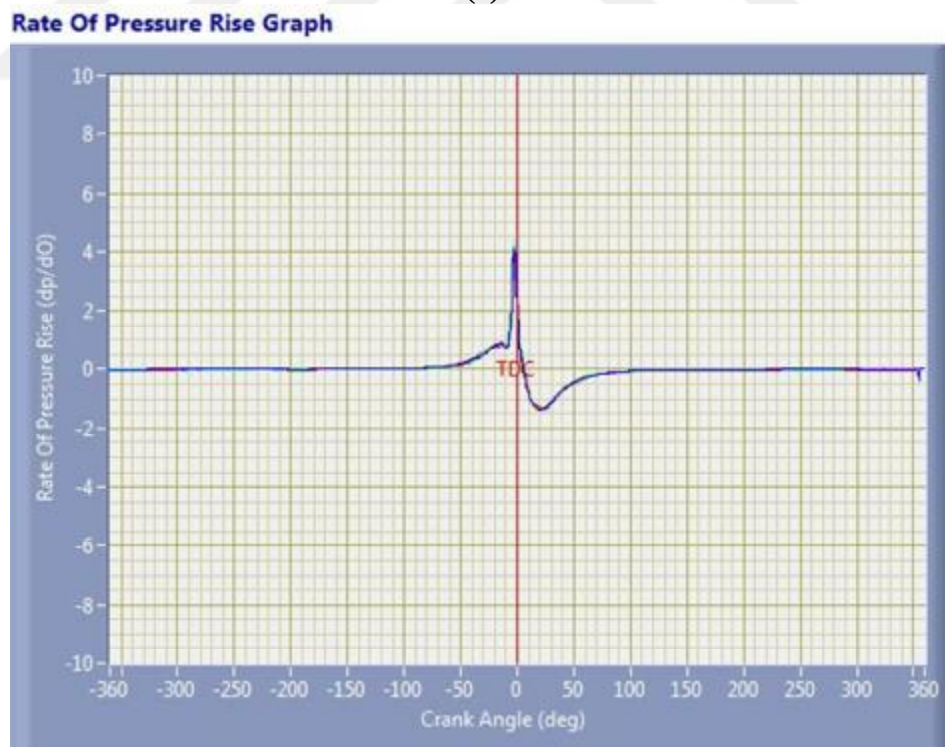
The combustion of diesel engine is a very complex phenomena which depends on many parameters such as fuel, engine design, ignition timing, compression ratio, injection profile and etc. diesel engine is generally partially premixed and partially diffusive. These phenomena is very complex mechanism to identify and it depends on fuel, engine design variables like compression ratio, fuel timing, and intake boosting the pressure, temperature and engine load.

Higher CR provides the reducing ignition delay and thus the combustion occur near the TDC (top dead center). The graphs show that the combustion of higher CR experiments occurs closer to TDC.

Cylinder pressure and rate of pressure rise graphs of D100, SB20, SB40, SB60, SB80, and SB100 at different CR under 60% load condition were presented in following figures. It can be seen from the graphs that CR increment increased peak cylinder pressure for all test fuels as it is expected. The increase of CR provides better mixing of fuel-air and leads to higher combustion temperature and according to analyses, biodiesel addition increased cylinder pressure.

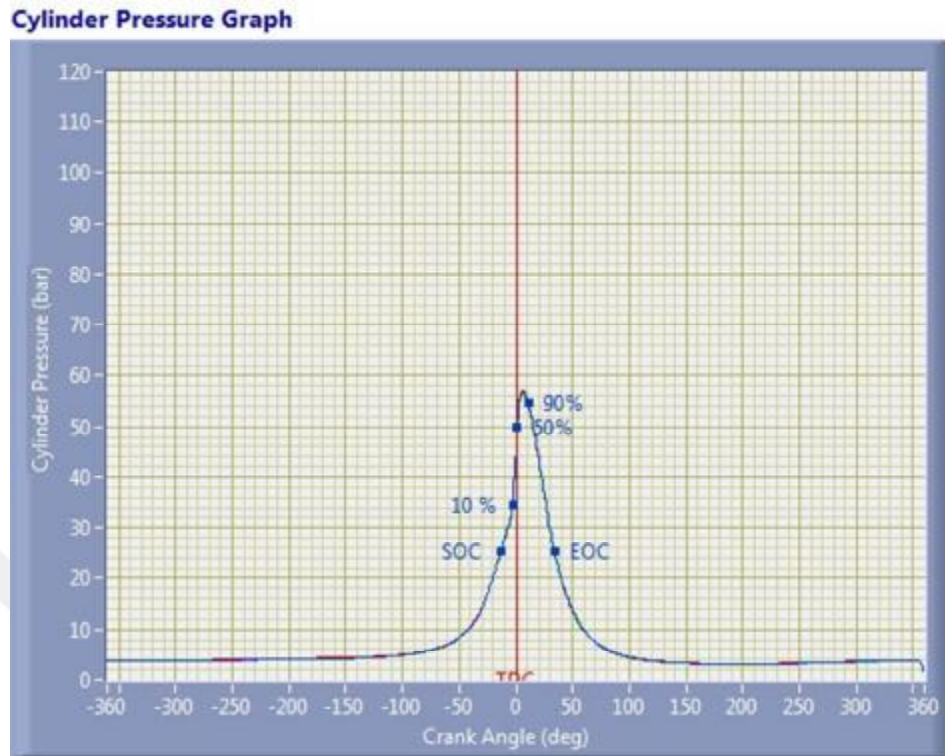


(a)

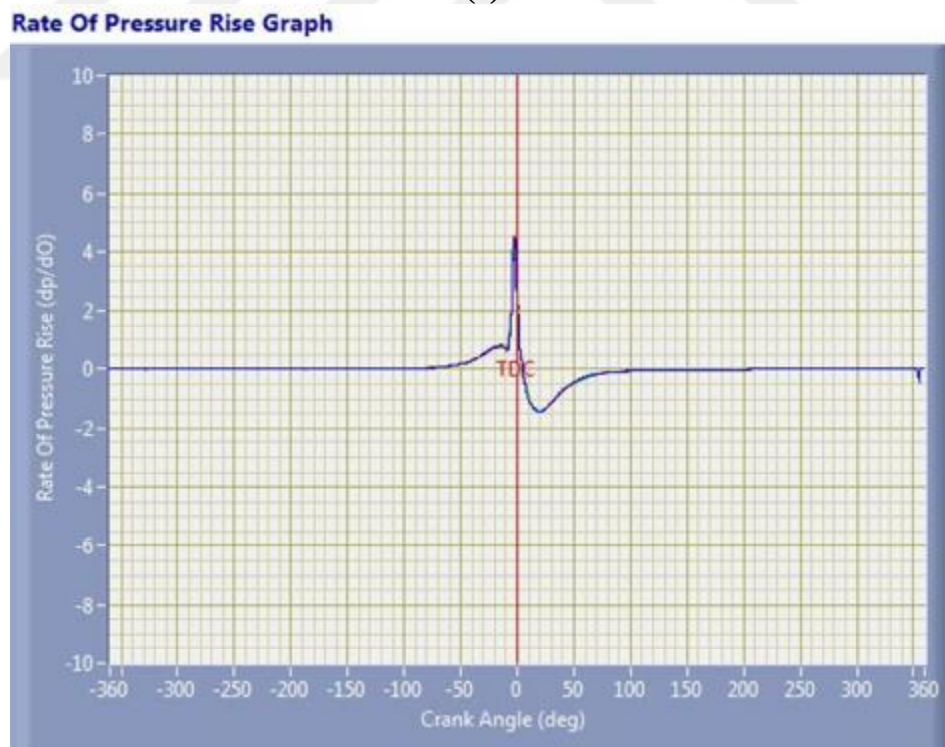


(b)

Figure 5.96. Cylinder pressure (a) and rate of pressure rise (b) graph of D100 under 60% load (CR 12:1)

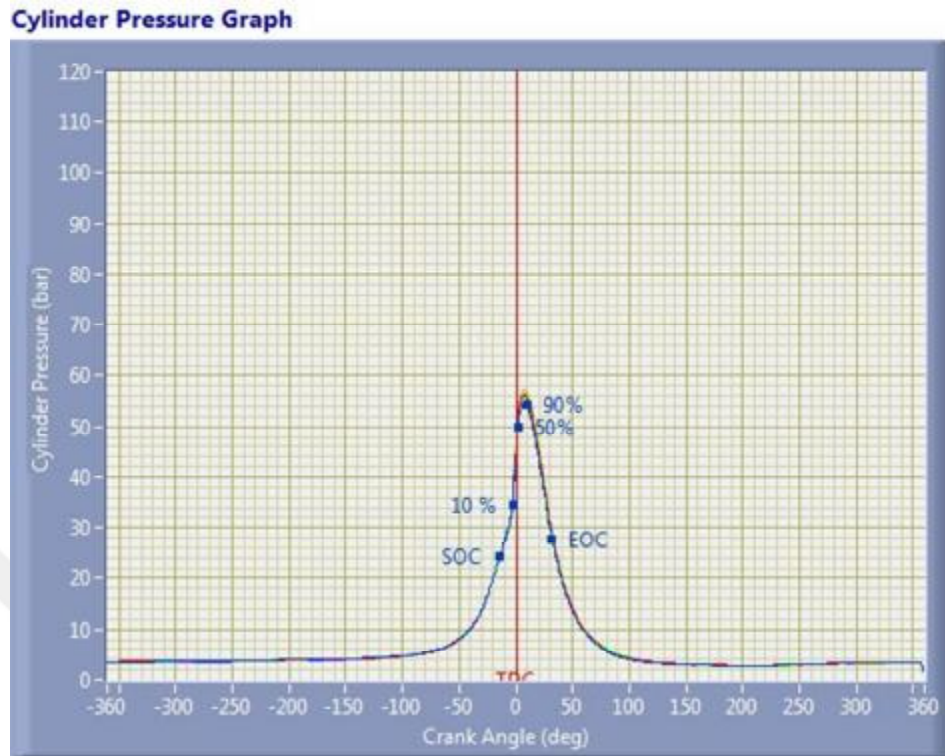


(a)

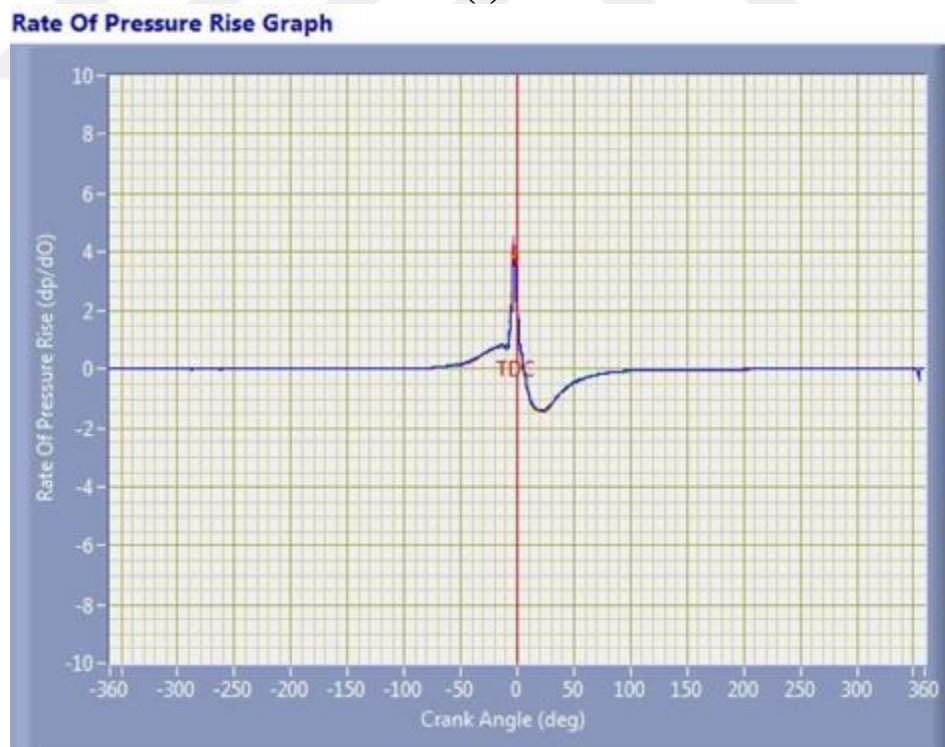


(b)

Figure 5.97. Cylinder pressure (a) and rate of pressure rise (b) graph of SB20 under 60% load (CR 12:1)

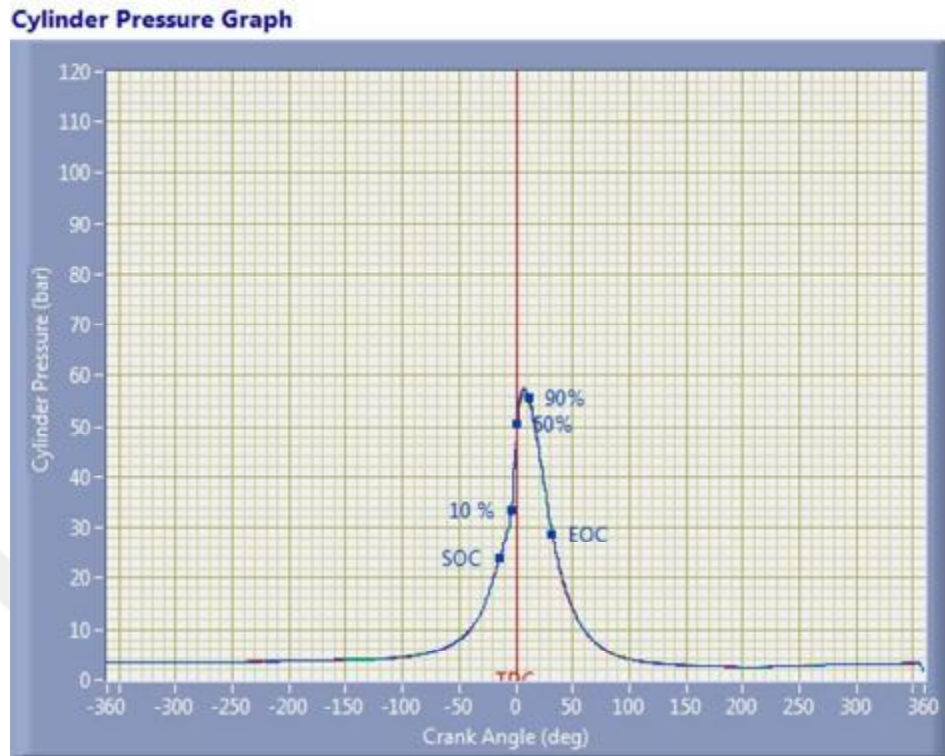


(a)

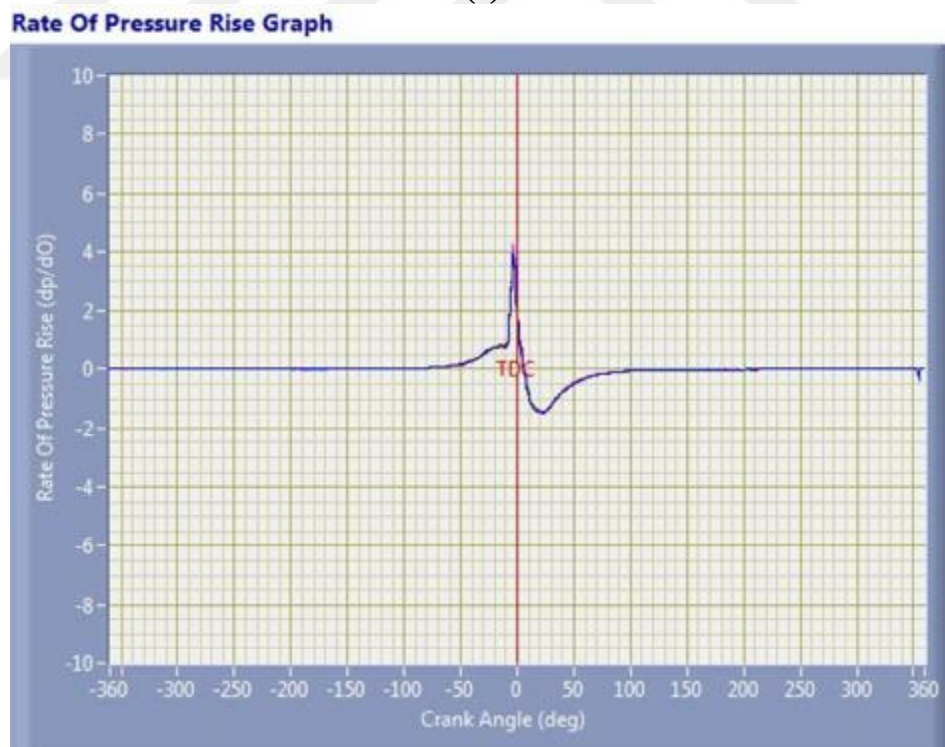


(b)

Figure 5.98. Cylinder pressure (a) and rate of pressure rise (b) graph of SB40 under 60% load (CR 12:1)



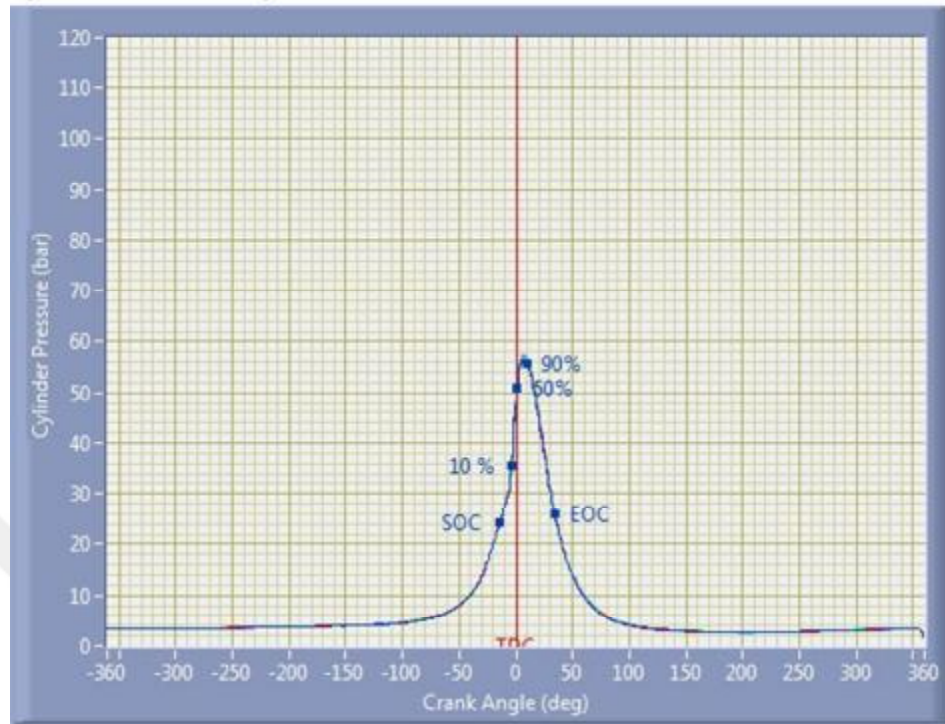
(a)



(b)

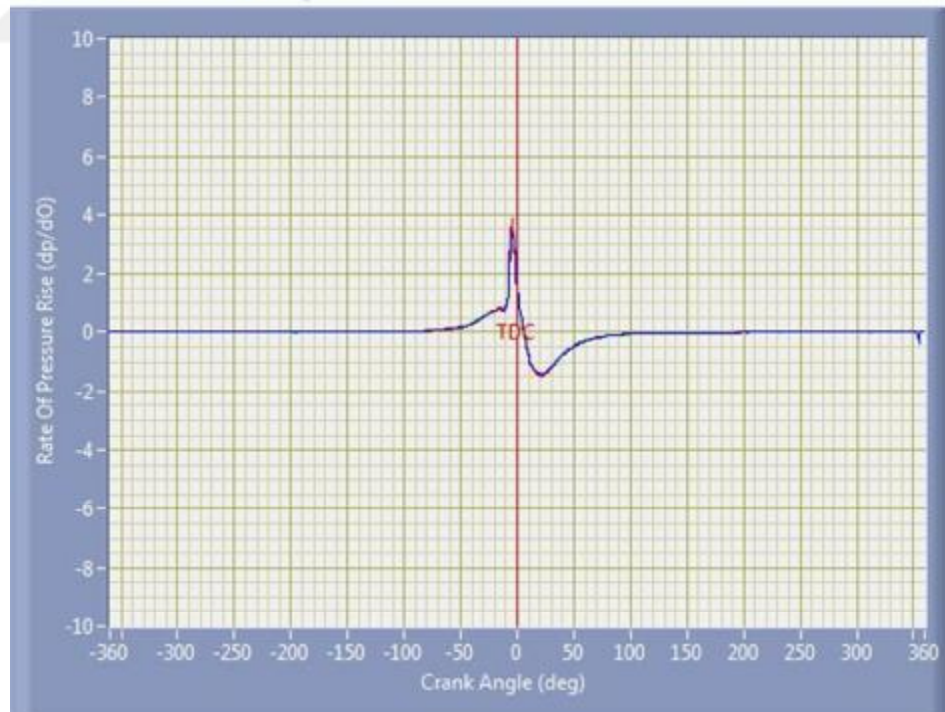
Figure 5.99. Cylinder pressure (a) and rate of pressure rise (b) graph of SB60 under 60% load (CR 12:1)

Cylinder Pressure Graph



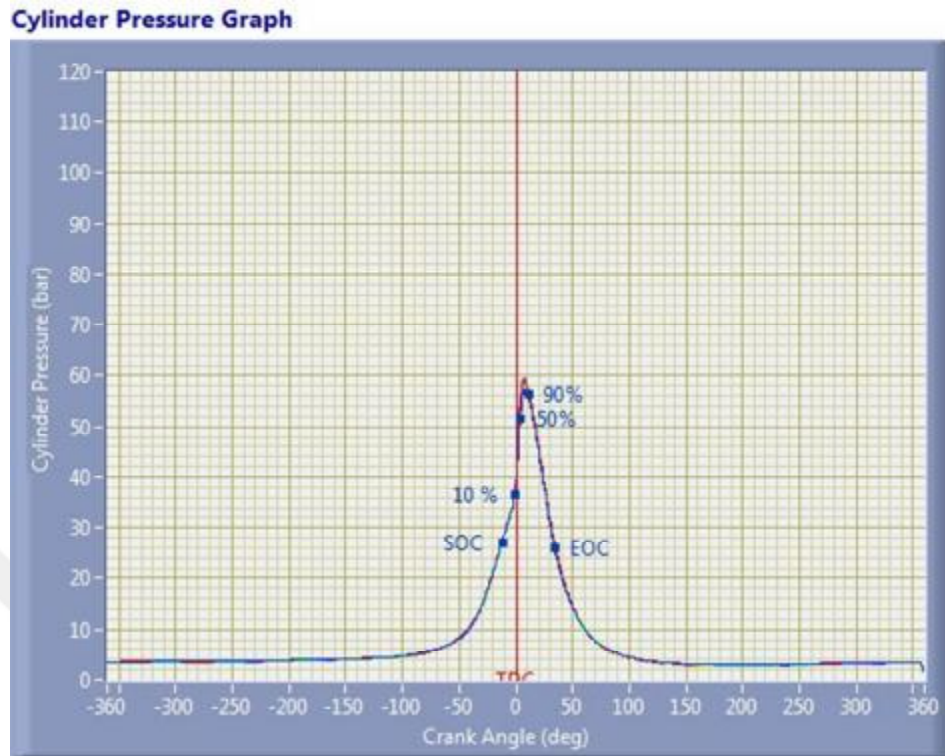
(a)

Rate Of Pressure Rise Graph

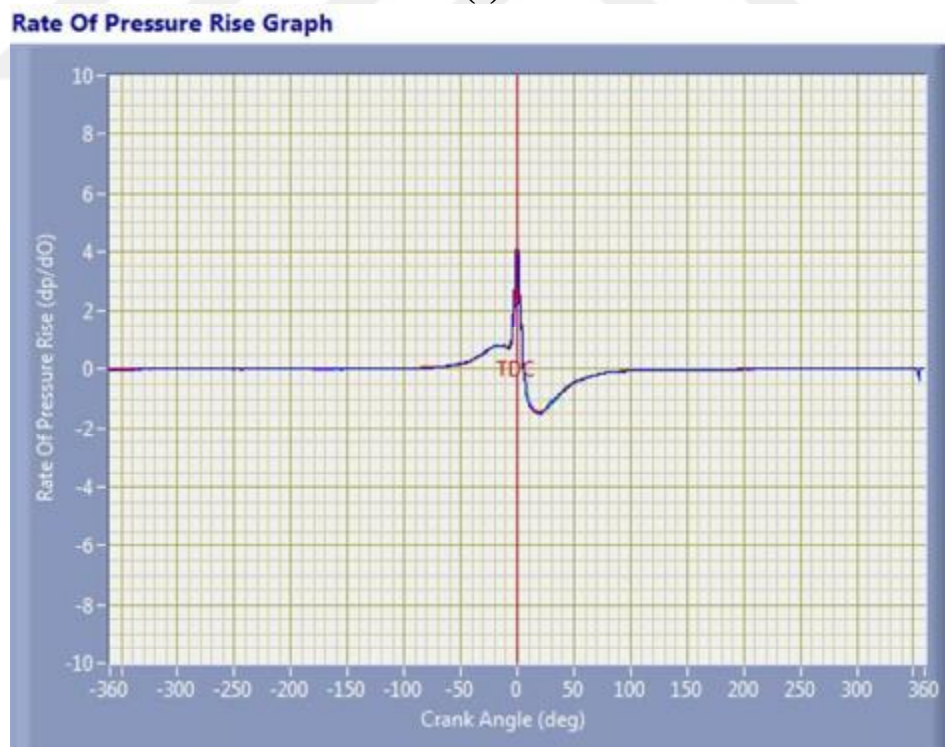


(b)

Figure 5.100. Cylinder pressure (a) and rate of pressure rise (b) graph of SB80 under 60% load (CR 12:1)

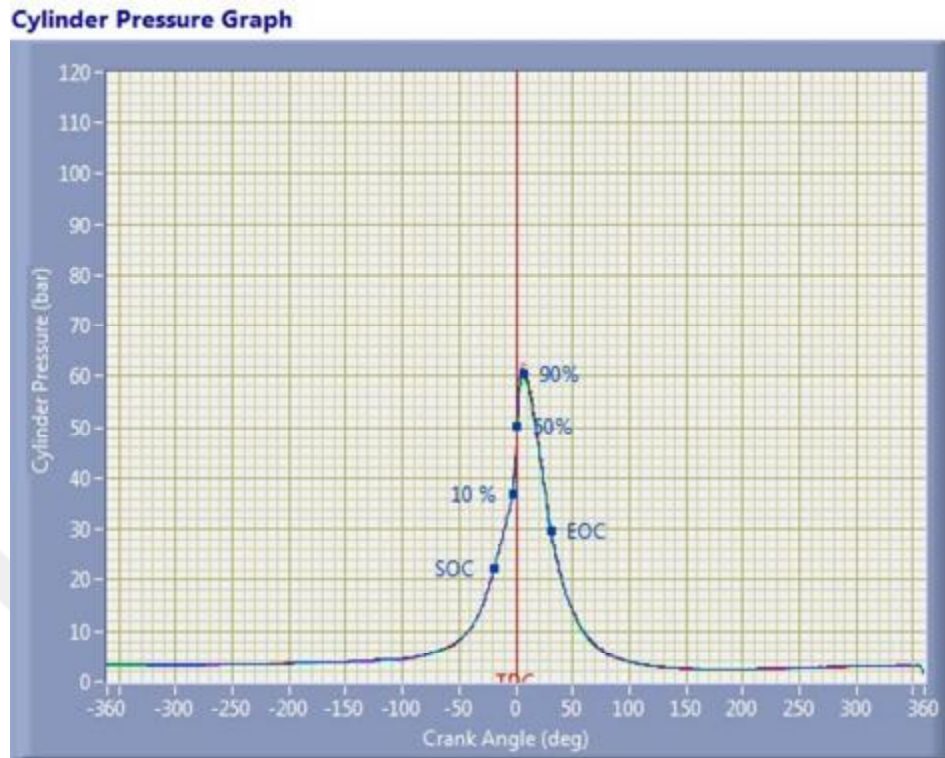


(a)

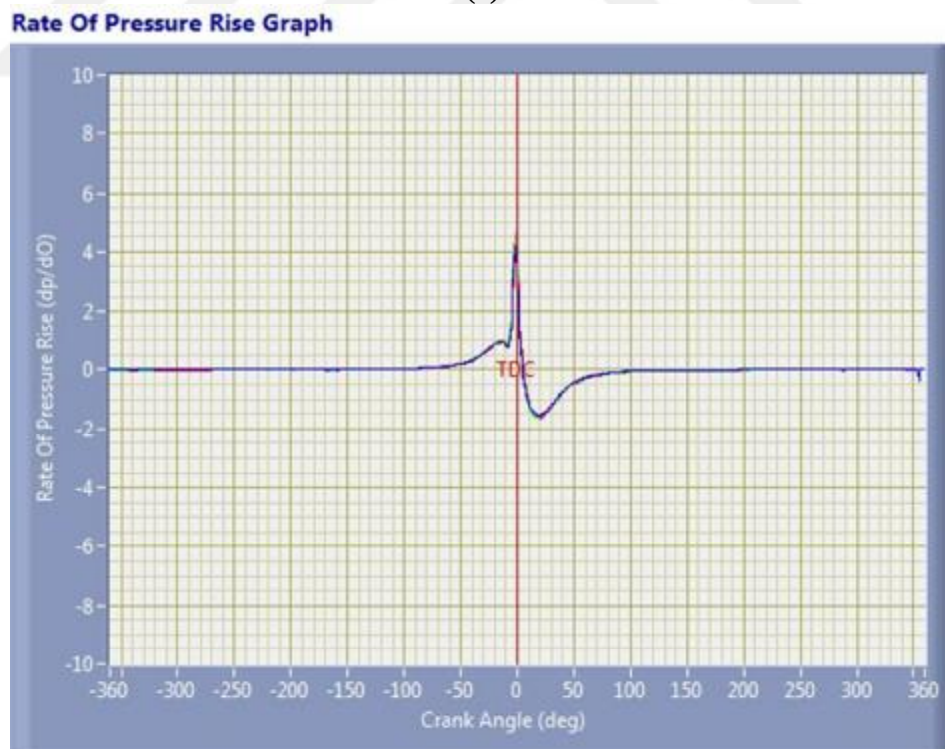


(b)

Figure 5.101. Cylinder pressure (a) and rate of pressure rise (b) graph of SB100 under 60% load (CR 12:1)

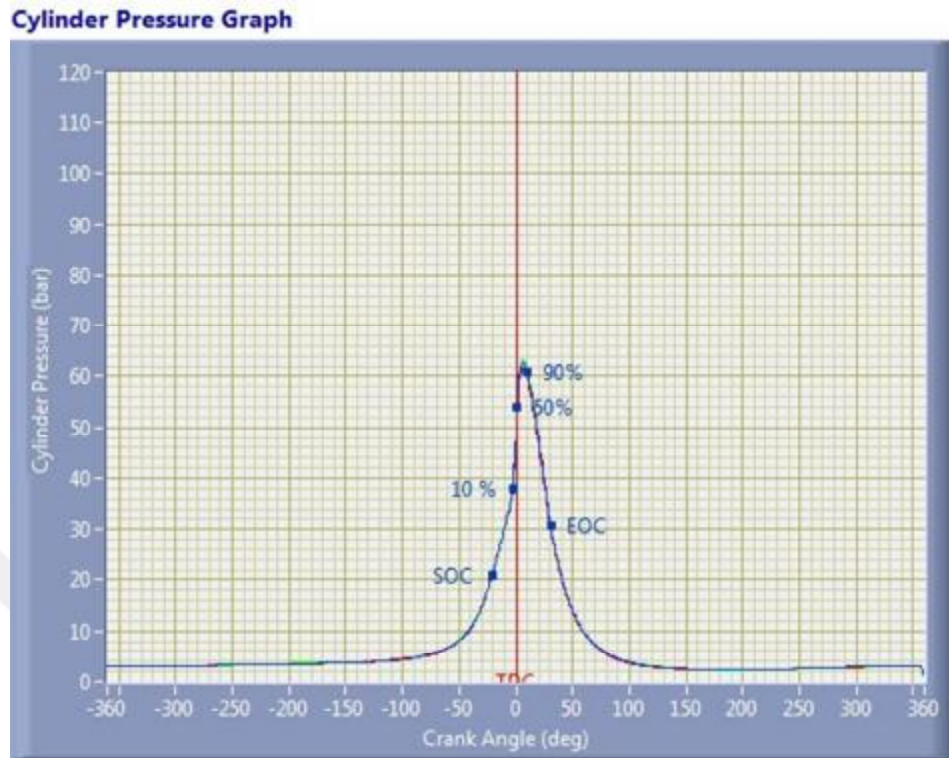


(a)

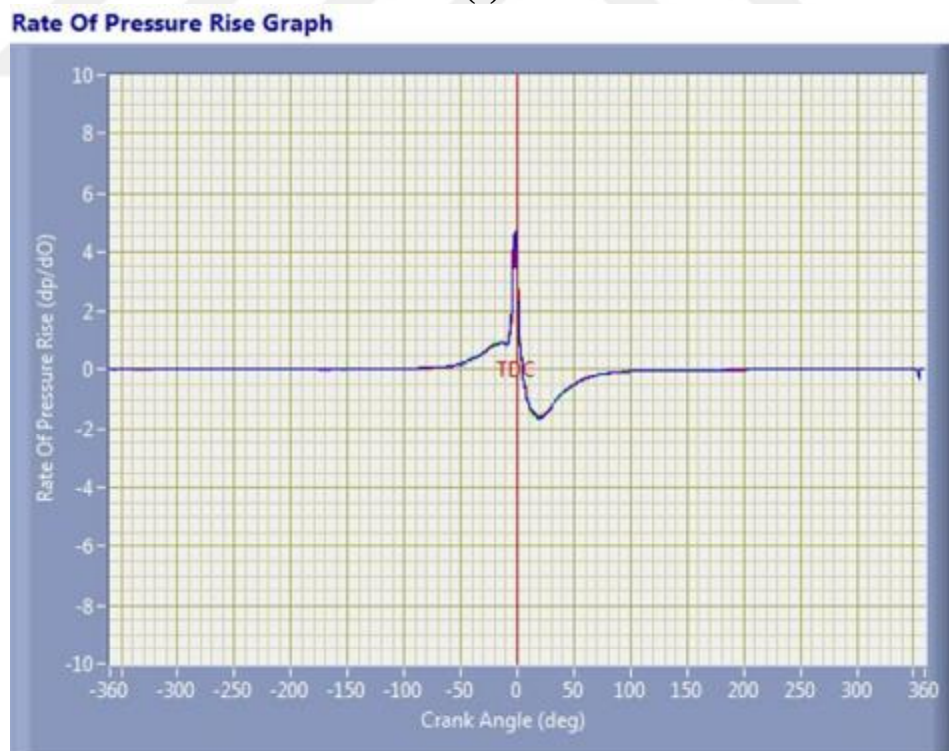


(b)

Figure 5.102. Cylinder pressure (a) and rate of pressure rise (b) graph of D100 under 60% load (CR 14:1)

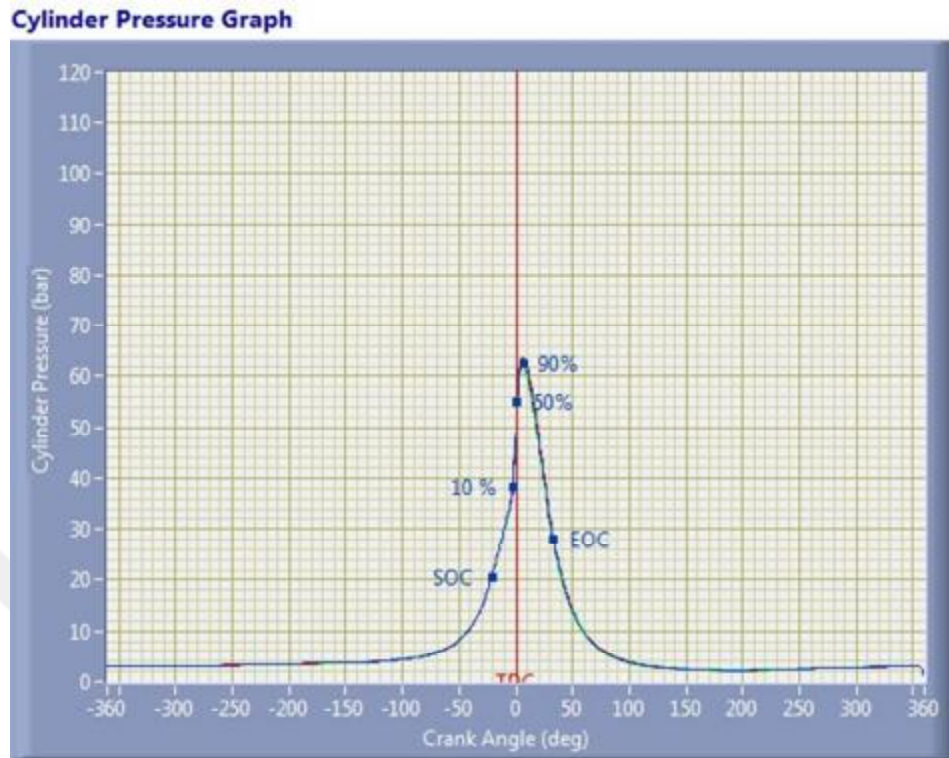


(a)

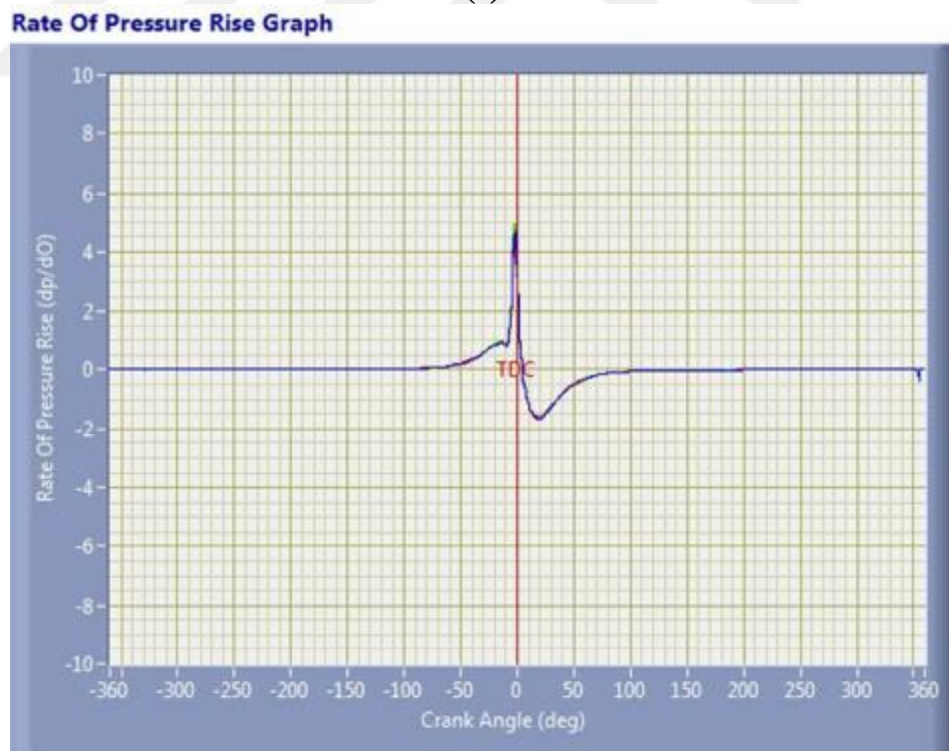


(b)

Figure 5.103. Cylinder pressure (a) and rate of pressure rise (b) graph of SB20 under 60% load (CR 14:1)

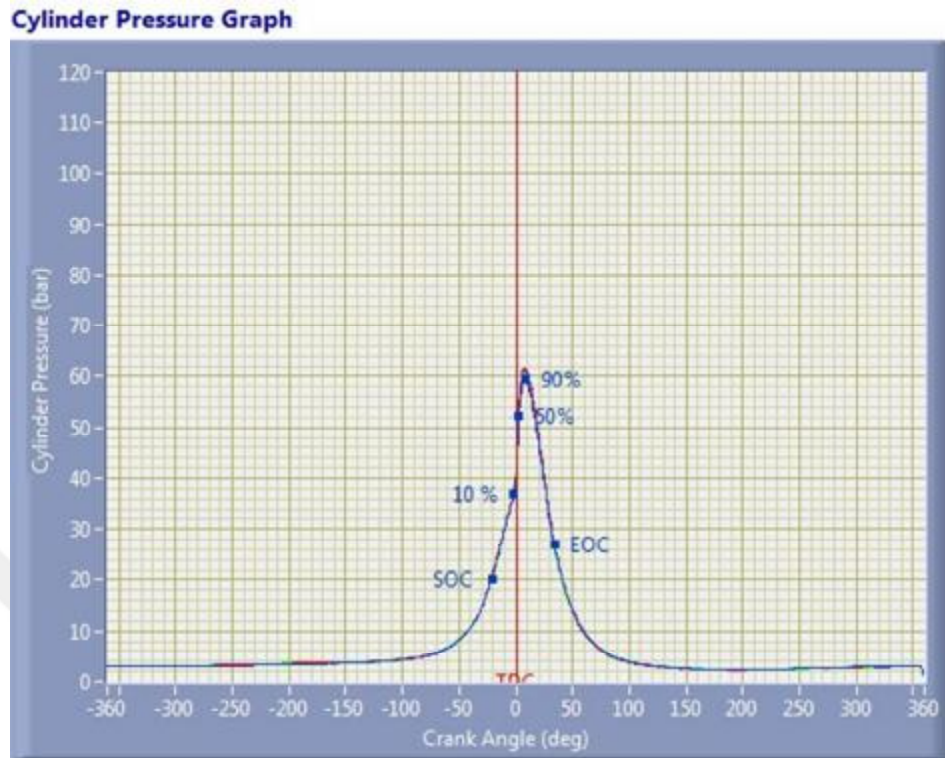


(a)

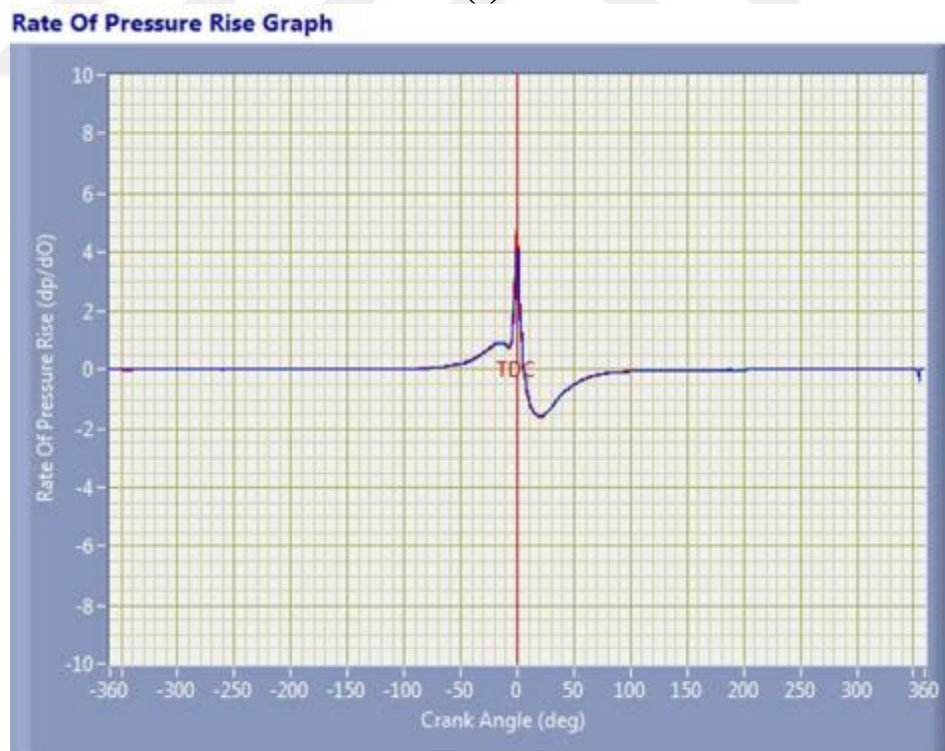


(b)

Figure 5.104. Cylinder pressure (a) and rate of pressure rise (b) graph of SB40 under 60% load (CR 14:1)

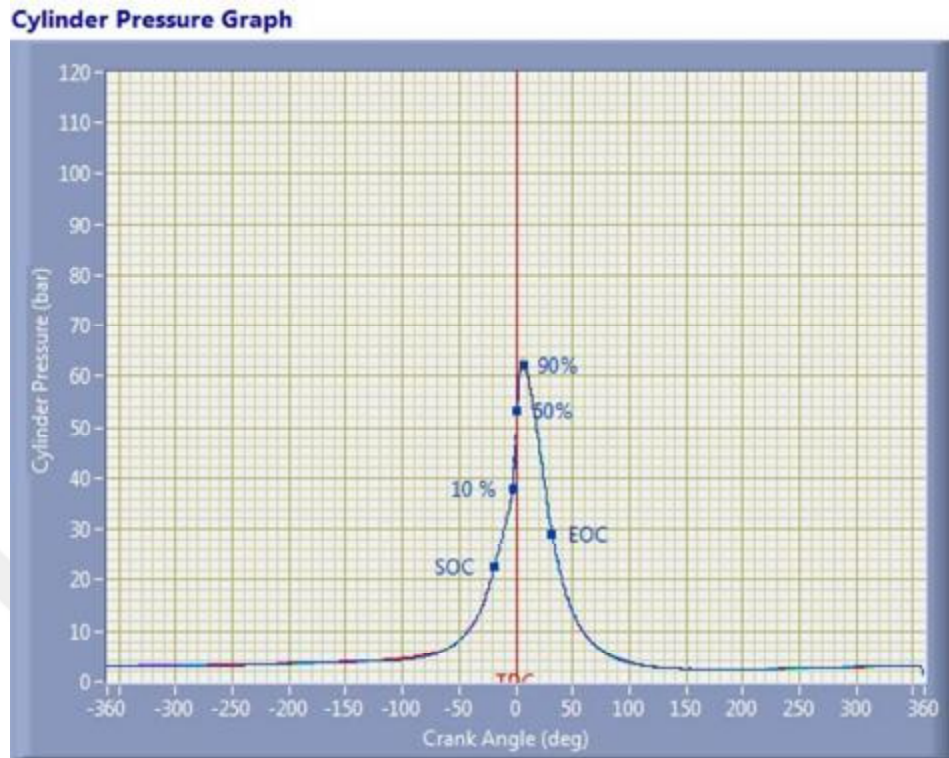


(a)

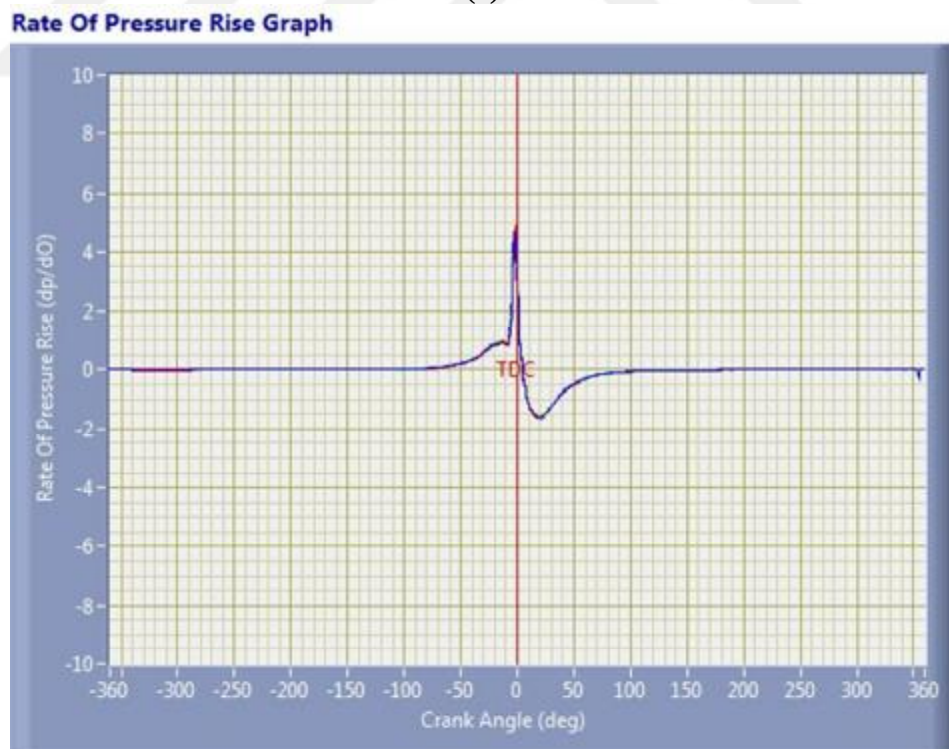


(b)

Figure 5.105. Cylinder pressure (a) and rate of pressure rise (b) graph of SB60 under 60% load (CR 14:1)

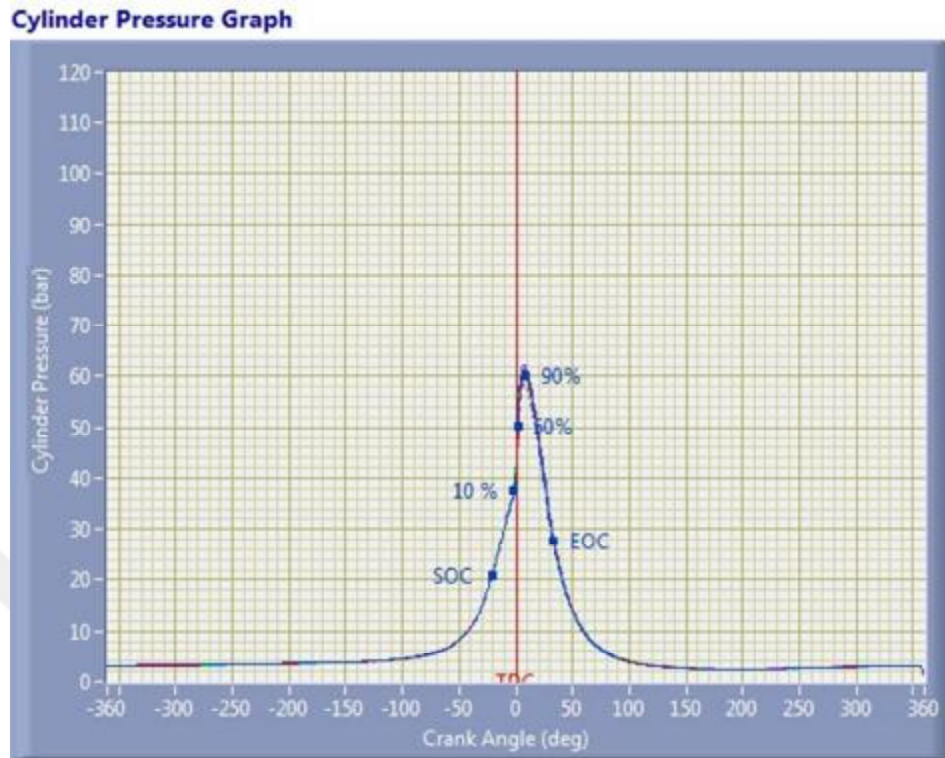


(a)

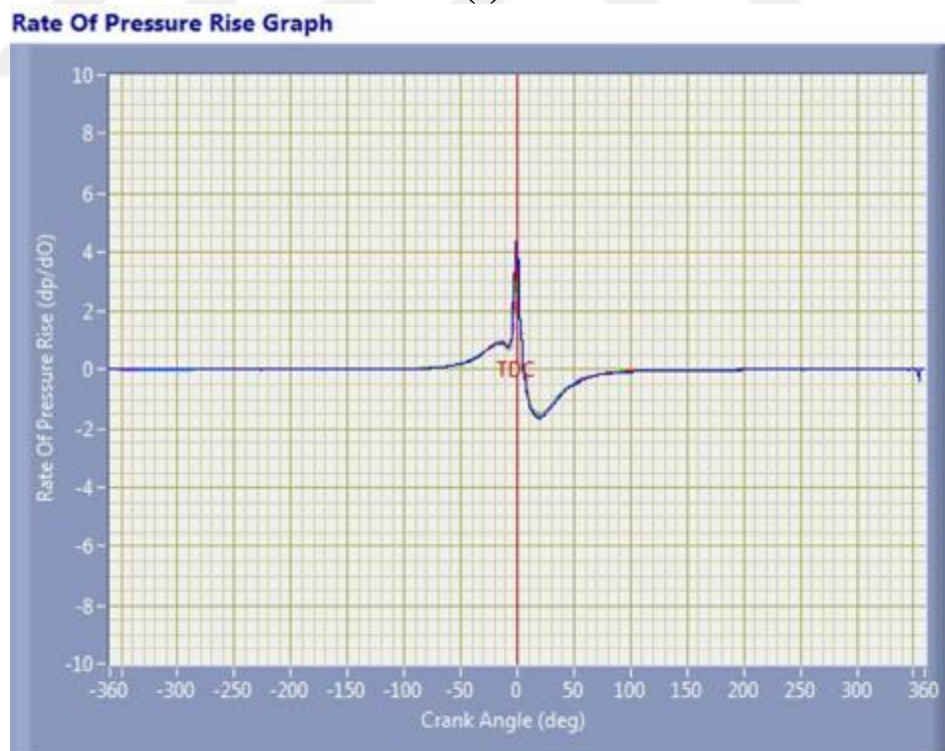


(b)

Figure 5.106. Cylinder pressure (a) and rate of pressure rise (b) graph of SB80 under 60% load (CR 14:1)

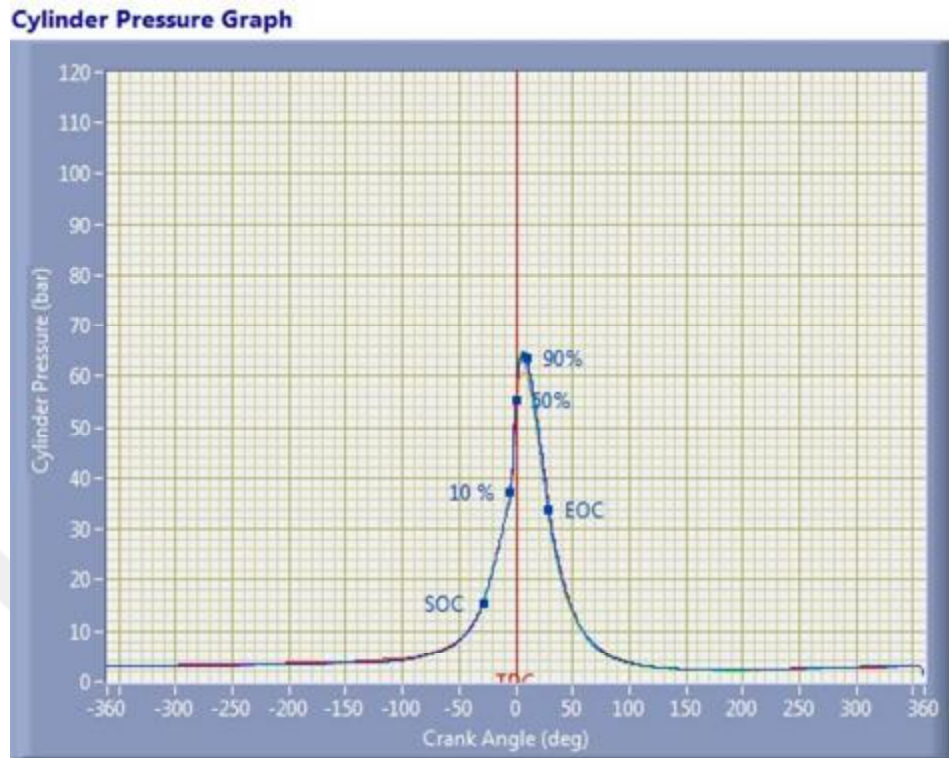


(a)

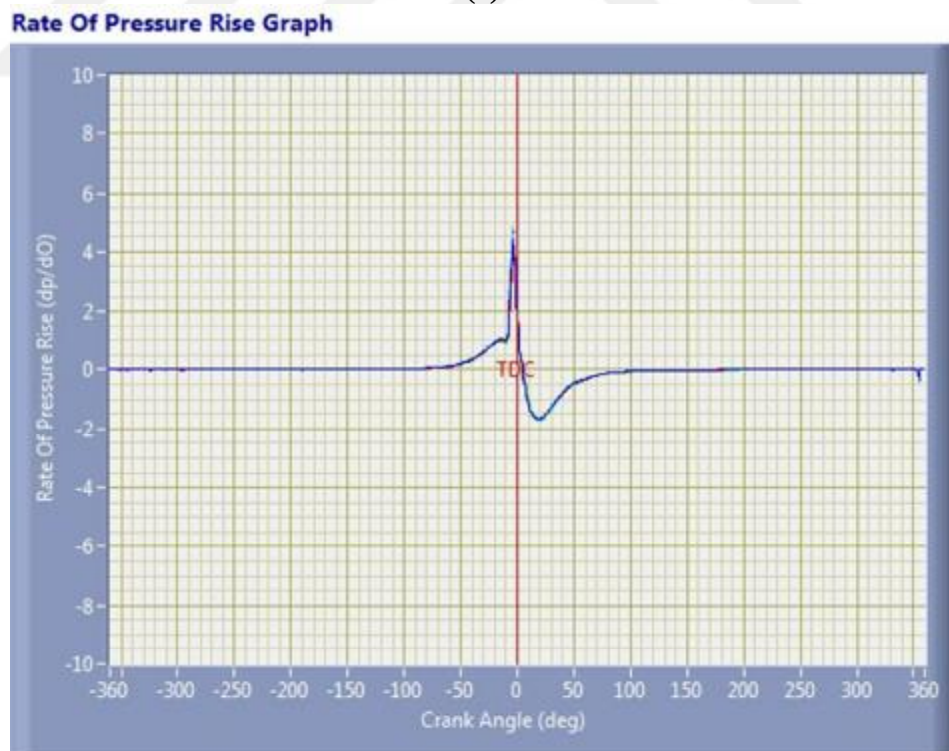


(b)

Figure 5.107. Cylinder pressure (a) and rate of pressure rise (b) graph of SB100 under 60% load (CR 14:1)

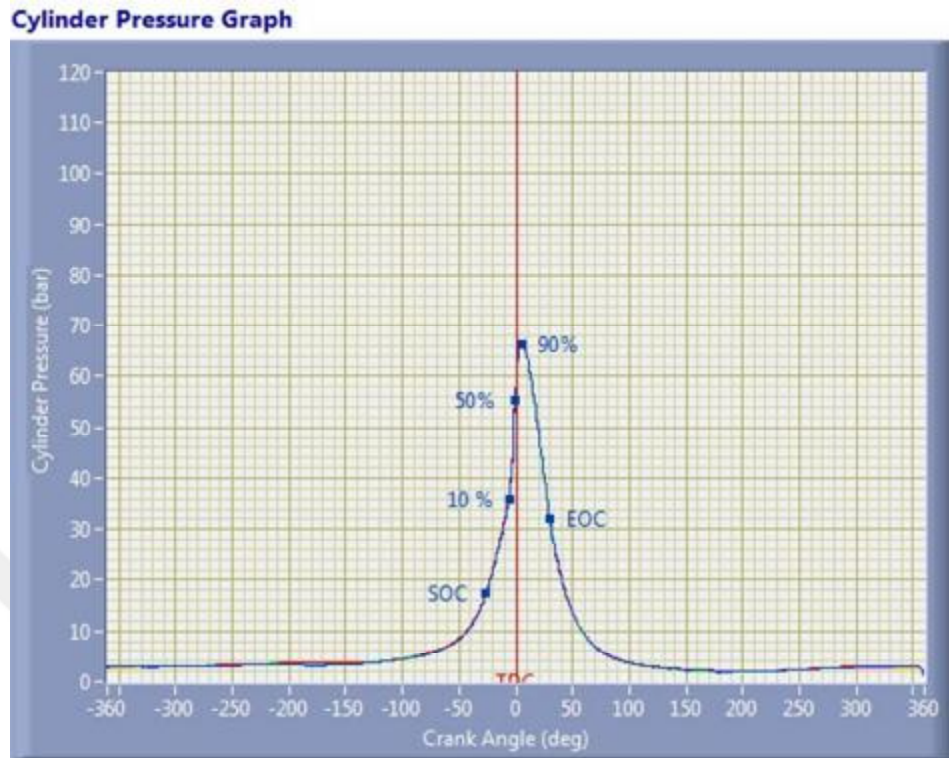


(a)

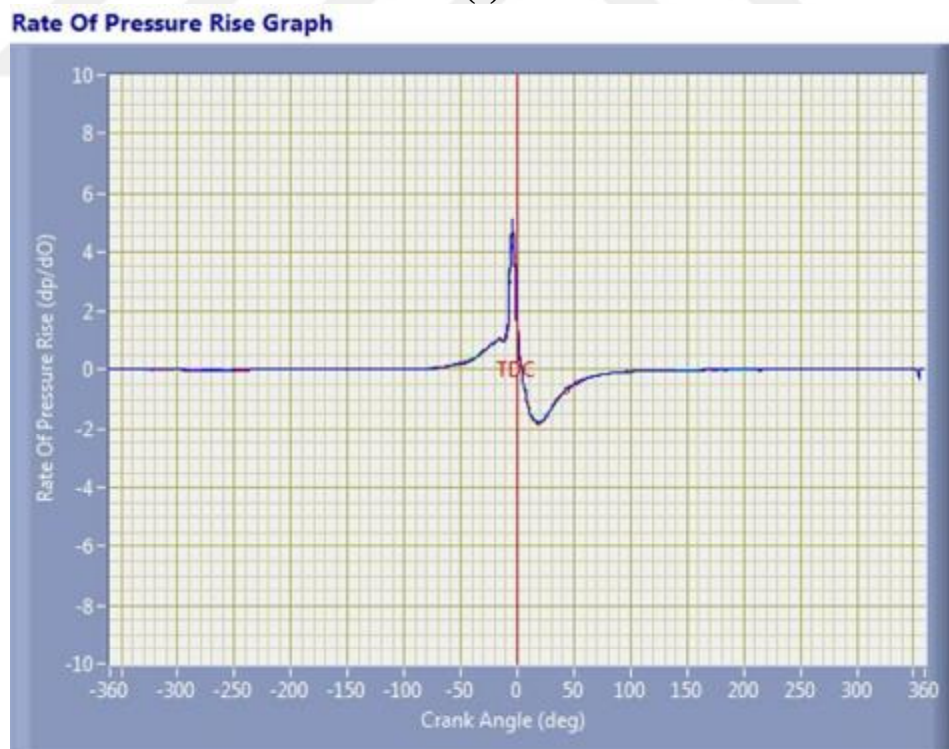


(b)

Figure 5.108. Cylinder pressure (a) and rate of pressure rise (b) graph of D100 under 60% load (CR 16:1)

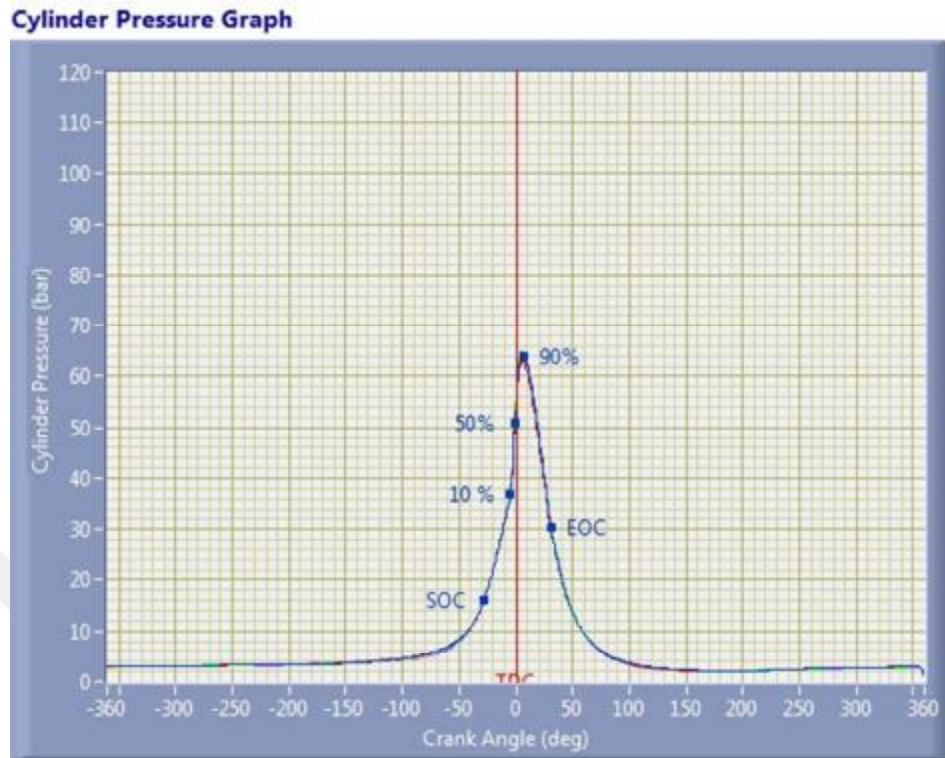


(a)

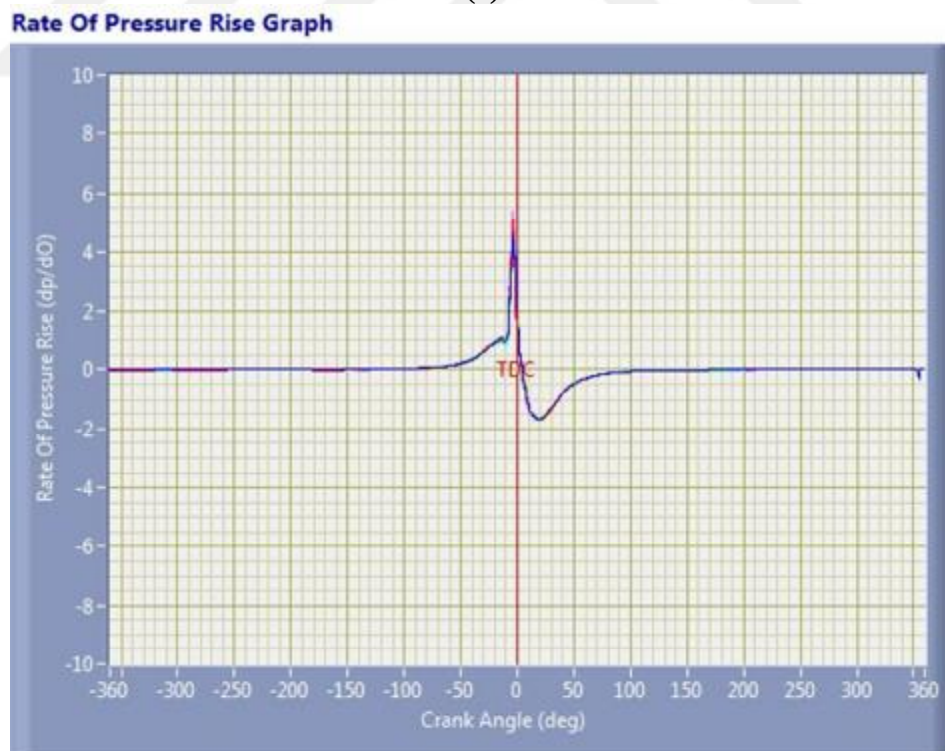


(b)

Figure 5.109. Cylinder pressure (a) and rate of pressure rise (b) graph of SB20 under 60% load (CR 16:1)

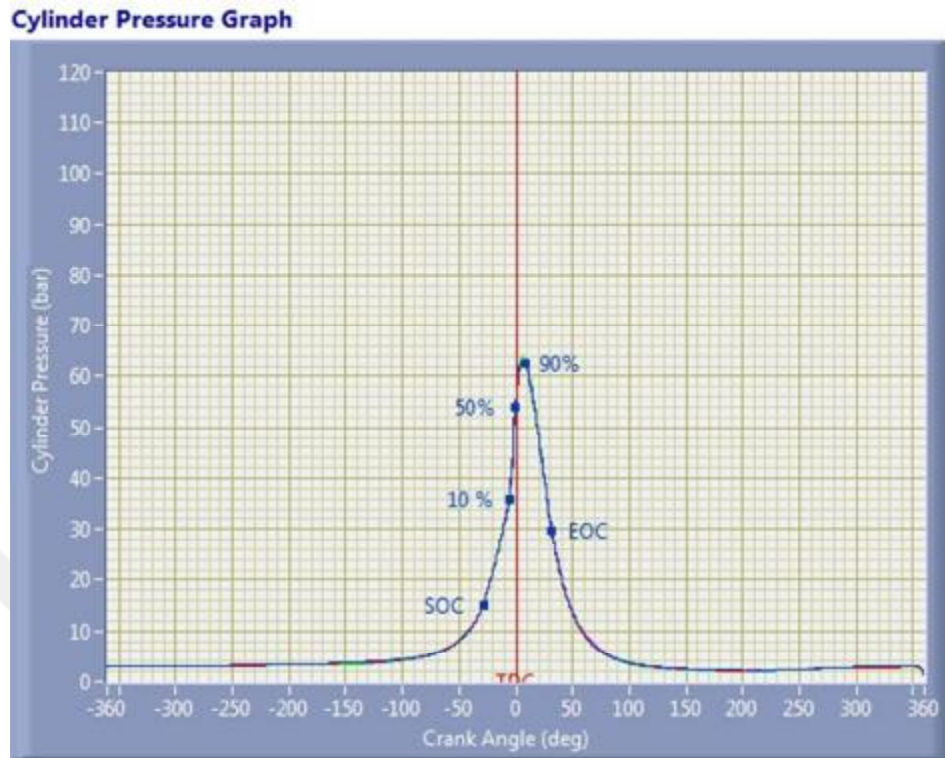


(a)

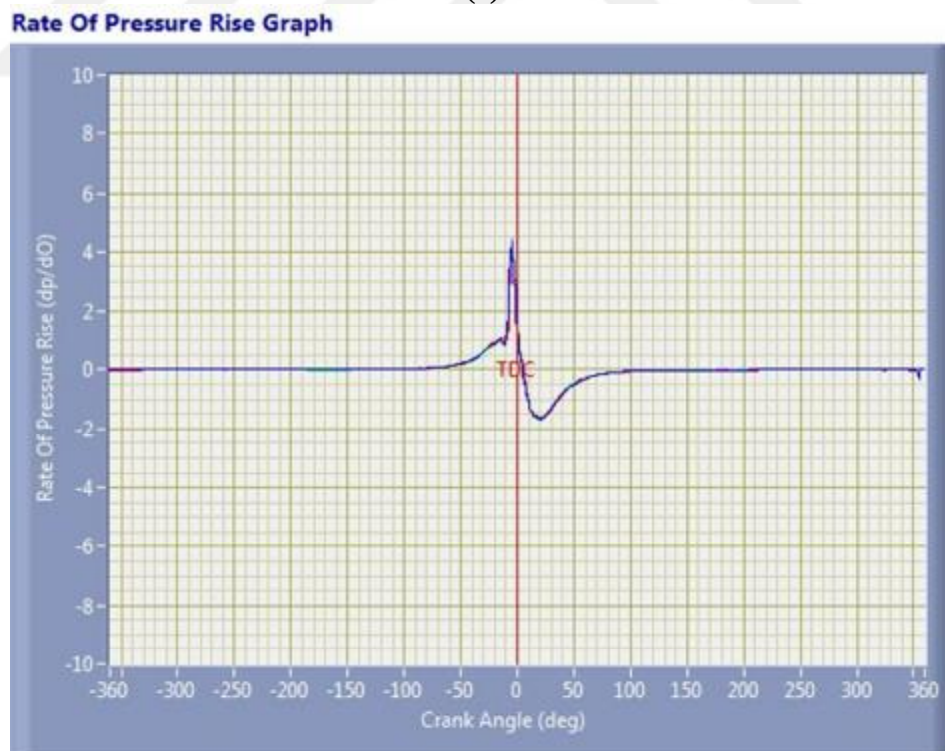


(b)

Figure 5.110. Cylinder pressure (a) and rate of pressure rise (b) graph of SB40 under 60% load (CR 16:1)

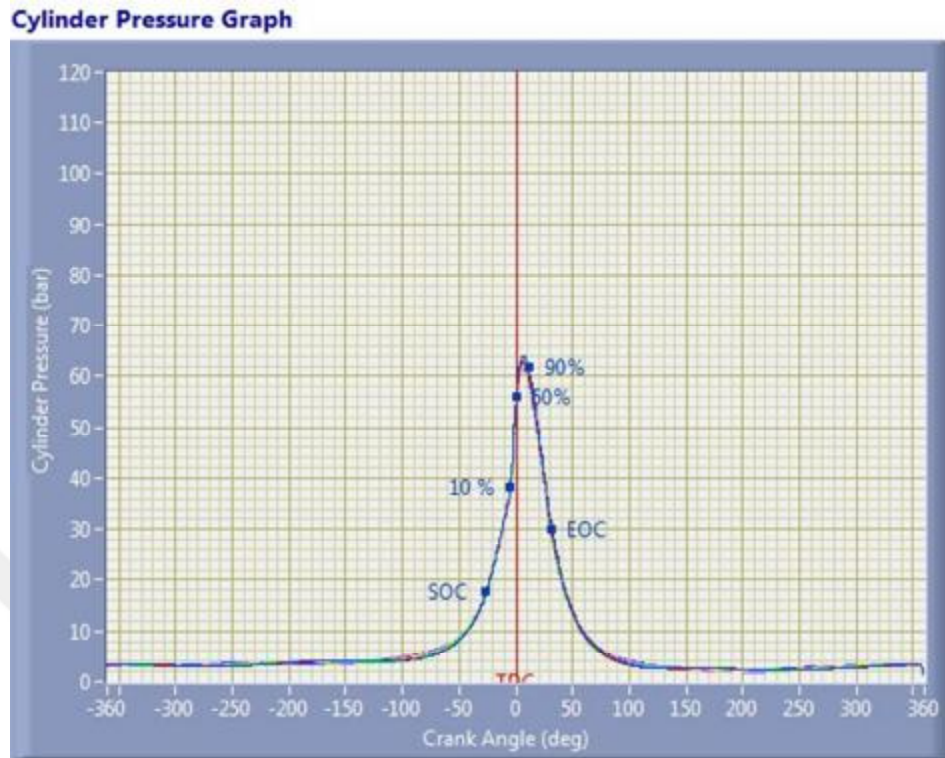


(a)

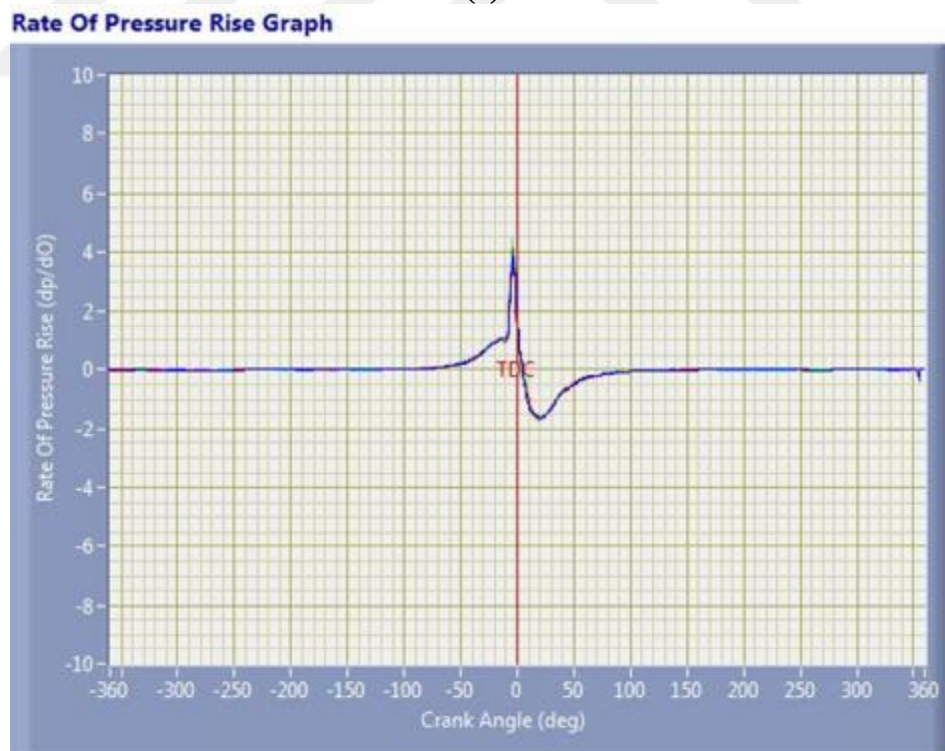


(b)

Figure 5.111. Cylinder pressure (a) and rate of pressure rise (b) graph of SB60 under 60% load (CR 16:1)

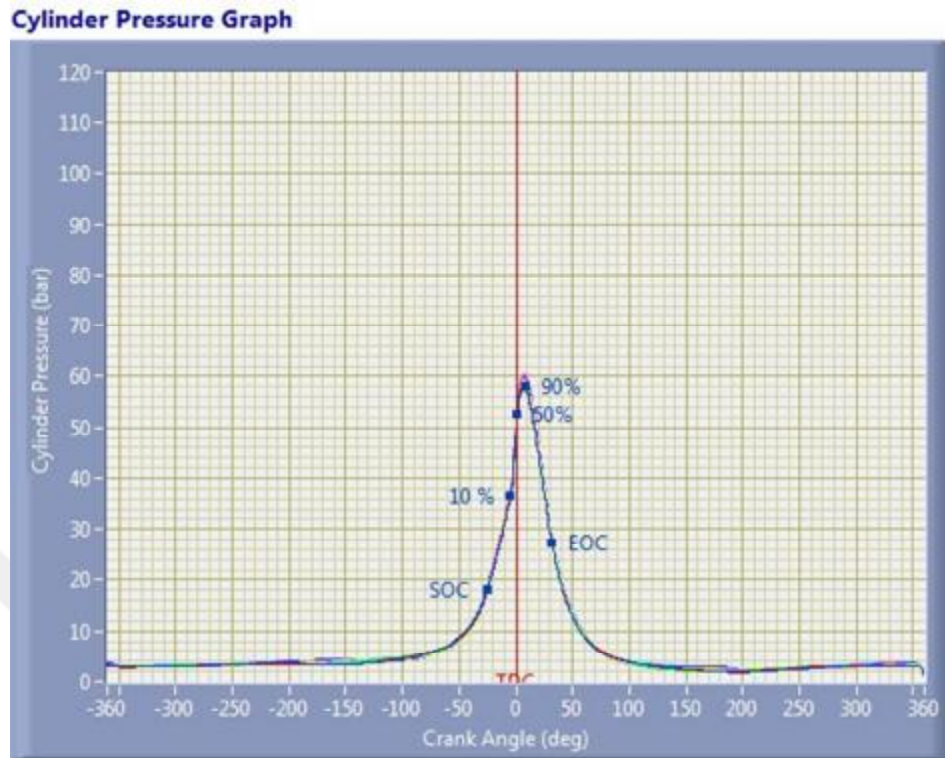


(a)

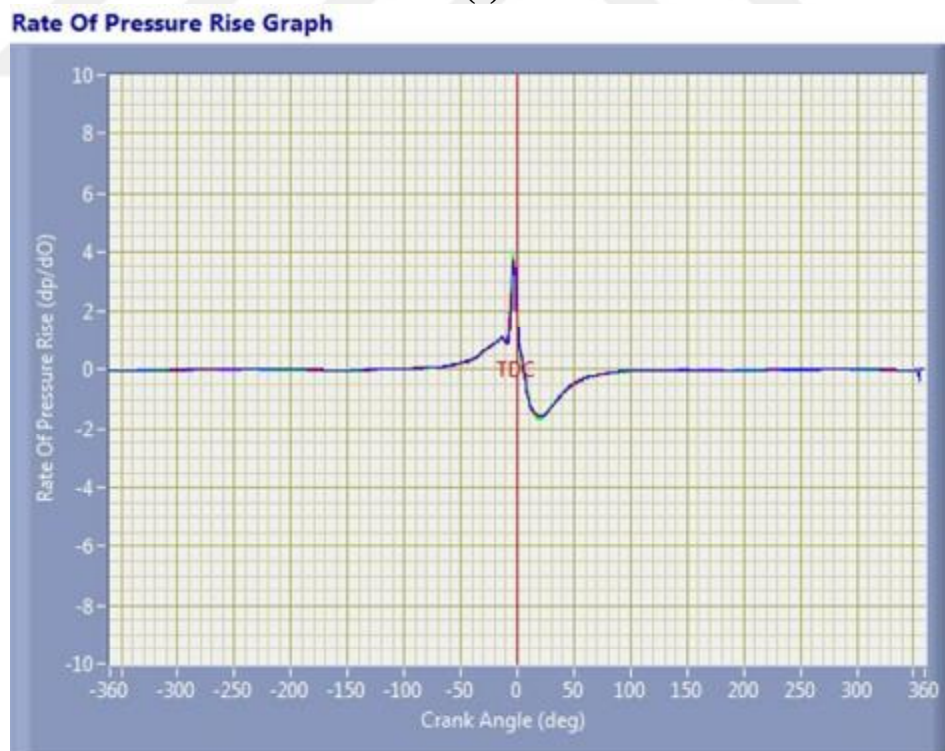


(b)

Figure 5.112. Cylinder pressure (a) and rate of pressure rise (b) graph of SB80 under 60% load (CR 16:1)



(a)



(b)

Figure 5.113. Cylinder pressure (a) and rate of pressure rise (b) graph of SB100 under 60% load (CR 16:1)



6. CONCLUSION

Alternative fuels to conventional diesel fuel have gained great attention mainly due to environmental issues. Therefore all effect of them must be well-known on diesel engines. The objective of this study was to investigate the effect of most popular alternative fuels; biodiesel, natural gas, and hydrogen on engine vibration, noise and exhaust emissions. The experiments were conducted on three different unmodified compression ignition engines to validate the results.

On the first engine, vibration analyses have been carried out in three orthogonal axes. Blends of sunflower, canola, and corn biodiesels were used to fuel the engine.

On second engine, vibration, noise and exhaust emission characteristics were observed. Hydrogen and natural gas with up to 40% biodiesel blends were also used to fuel this engine

On the last engine, all test biodiesel fuels were used in order to observe engine combustion characteristic as well as noise and vibration characteristics.

According to experiments and results, following summarizes were brought out:

- SPL and vibration acceleration of the test engines significantly increased with engine speed.
- The dominant frequency was regardless of fuel type. It affected by engine speed due to upward and downward piston movement.
- Averagely, compared to low sulphur diesel fuel, vibration and SPL decrement was observed with biodiesel usage.
- SPL and vibration acceleration can be predicted with an acceptable accuracy with the usage of linear and non-linear regression.
- SPL and vibration acceleration values reduced with hydrogen and natural gas addition into intake air.

- Increasing compression ratio was also cause to decrement of noise and vibration level whereas they significantly increased with loading the engine



REFERENCES

- ABAGNALE, C., CAMERETTI, M.C., DE SIMIO, L., GAMBINO, M., IANNACCONE, S., and TUCCILLO, R., 2014. Combined Numerical-Experimental Study of Dual Fuel Diesel Engine. *Energy Procedia*, 45: 721–730.
- ABDULVAHİTOĞLU, A., 2009. Performance and Exhaust Emission Characteristics of a CI Engine Fuelled With Syntesized Fuel Blends. Ç.U. Department of Mechanical Engineering - Phd Thesis 221p.
- ALI, O. M., MAMAT, R., ABDULLAH, N. R. and ABDULLAH, A. A., 2016. Analysis of Blended Fuel Properties and Engine Performance with Palm Biodiesel–Diesel Blended Fuel. *Renew. Energy*, 86: 59–67.
- ALPTEKIN, E., CANAKCI, M., OZSEZEN, A. N., TURKCAN, A. and SANLI, H., 2015. Using Waste Animal Fat Based Biodiesels–Bioethanol–Diesel Fuel Blends in a DI Diesel Engine. *Fuel*, 157: 245–254.
- ARBAB, M. I., MASJUKI, H.H., VARMAN, M., KALAM, M.A., IMTENAN, S., and SAJJAD, H., 2013. Fuel Properties, Engine Performance and Emission Characteristic of Common Biodiesels as a Renewable and Sustainable Source of Fuel. *Renewable and Sustainable Energy Reviews*, 22: 133–147.
- ATABANI, A.E., SILITONGA, A.S., BADRUDDIN, I.A., MAHLIA, T.M.I., MASJUKI, H.H., and MEKHILEJ, S., 2012. A Comprehensive Review on Biodiesel as an Alternative Energy Resource and its Characteristics. *Renewable and Sustainable Energy Reviews*, 16: 2070–2093.
- ATALAY, M., ANAFARTA, N. and SARVAN, F., 2013. The Relationship between Innovation and Firm Performance: An Empirical Evidence from Turkish Automotive Supplier Industry. *Procedia - Social and Behavioral Sciences*, 75: 226–235.
- BALAT, M. and BALAT, H., 2010. Progress in Biodiesel Processing. *Applied Energy*, 87: 1815–1835.

- BANERJEE, R., ROY, S. and BOSE, P. K., 2015. Hydrogen-EGR Synergy as a Promising Pathway to Meet the PM–NO_x–BSFC Trade-Off Contingencies of the Diesel Engine: A Comprehensive Review. *International Journal of Hydrogen Energy*, 40: 12824–12847.
- BEHÇET, R., OKTAY, H., ÇAKMAK, A. and AYDIN, H., 2015. Comparison of Exhaust Emissions of Biodiesel–Diesel Fuel Blends Produced From Animal Fats. *Renewable and Sustainable Energy Reviews*, 46: 157–165.
- BENDU, H. and MURUGAN, S., 2014. Homogeneous Charge Compression Ignition (HCCI) Combustion: Mixture Preparation and Control Strategies in Diesel Engines. *Renewable and Sustainable Energy Reviews*, 38: 732–746.
- BERGTHORSON, J. M. and THOMSON, M. J., 2015. A Review of the Combustion and Emissions Properties of Advanced Transportation Biofuels and Their Impact on Existing and Future Engines. *Renewable and Sustainable Energy Reviews*, 42: 1393–1417.
- BILGILI M, and SAHIN B., 2010. Comparative Analysis of Regression and Artificial Neural Network Models for Wind Speed Prediction. *Meteorology Atmospheric Physics*, 109:61–72.
- BROOK, B. W., ALONSO, A., MENELEY, D.A., MISAK, J., BLEES, T., and VAN ERP, J.B., 2014. Why Nuclear Energy is Sustainable and has to be Part of the Energy Mix. *Sustainable Materials and Technologies*, 1(2): 8–16.
- BRUEL and KJAER, 1984. *Mechanical Vibration and Shock Measurements*. 370p.
- CAN, Ö., 2014. Combustion Characteristics, Performance and Exhaust Emissions of a Diesel Engine Fuelled with a Waste Cooking Oil Biodiesel Mixture. *Energy Conversion and Management*, 87: 676–686.
- CHEN, J., RANDALL, R. B. and PEETERS, B., 2016. Advanced Diagnostic System for Piston Slap Faults in IC Engines, Based on the Non-stationary Characteristics of the Vibration Signals. *Mechanical Systems and Signal Processing*, In press: 1–21.
- CHIARI, L. and ZECCA, A., 2011. Constraints of Fossil Fuels Depletion on Global Warming Projections. *Energy Policy*, 39: 5026–5034.

- CZECH, P., LAZARZ, B., MADEJ, H., and WOJNAR, G., 2010. Vibration Diagnosis of Car Motor Engines. *Acta Technica Corviniensis*, 3:37–42.
- DABROWSKI, Z. and KOMORSKA, I., 2012. Identification of Engine Vibroacoustic Model for Diagnostics of Mechanical Defects. *Proceedings of PACAM XII*;2–6
- DEB, M., SASTRY, G. R. K., BOSE, P. K., and BANERJEE, R., 2015. An experimental study on combustion, performance and emission analysis of a single cylinder, 4-stroke DI-diesel engine using hydrogen in dual fuel mode of operation. *International Journal of Hydrogen Energy*, 40:8586–98.
- DIMARAGONAS, A. D., 1992. *Vibration for Engineers*. Prentice-Hall, USA, 749p.
- DUKKIPATI, R. V., 2006. *Advanced Mechanical Vibrations*. Alpha Science International Ltd, Oxford, 468p.
- ENGERER, H. and HORN, M., 2010. Natural gas vehicles: An Option for Europe. *Energy Policy*, 38: 1017–1029.
- GENG, Z., CHEN, J. and BARRY HULL, J., 2003. Analysis of Engine Vibration and Design of an Applicable Diagnosing Approach. *International Journal of Mechanical Sciences*, 45: 1391–1410.
- GHAREHGHANI, A., HOSSEINI, R., MIRSALEM, M., JAZAYERI, S. A. and YUSAF, T., 2015. An Experimental Study on Reactivity Controlled Compression Ignition Engine Fuelled with Biodiesel/Natural Gas. *Energy*, 89: 558–567.
- GIAKOUMIS, E. G., DIMARATOS, A. M. and RAKOPOULOS, C. D., 2011. Experimental Study of Combustion Noise Radiation During Transient Turbocharged Diesel Engine Operation. *Energy*, 36: 4983–4995.
- GIAKOUMIS, E. G., RAKOPOULOS, D. C. and RAKOPOULOS, C. D., 2016. Combustion Noise Radiation During Dynamic Diesel Engine Operation Including Effects of Various Biofuel Blends: A Review. *Renewable and Sustainable Energy Reviews*, 54: 1099–1113.
- GRAVALOS, I., LOUTRIDIS, S., MOSHOV, D., GIALAMAS, T., KATERIS, D., TSIROPOULOS, Z., AND XYRADAKIS, P., 2013. Detection of Fuel Type on a Spark Ignition Engine From Engine Vibration Behaviour. *Fuel*, 54: 171-175.

- HOLM, M., GARCIA, A. C., ADAMSON, G. and WANG, L., 2014. Adaptive Decision Support for Shop-floor Operators in Automotive Industry. *Procedia CIRP*, 17: 440–445.
- HOW, H. G., MASJUKI, H. H., KALAM, M. a. and TEOH, Y. H., 2014. An Investigation of the Engine Performance, Emissions and Combustion Characteristics of Coconut Biodiesel in a High-Pressure Common-Rail Diesel Engine. *Energy*, 69: 749–759.
- IPCI, D. and KARABULUT, H., 2015. Thermodynamic and Dynamic Modeling of a Single Cylinder Four Stroke Diesel Engine. *Applied Mathematical Modelling*, In press, 1–13.
- JHANG, S.R., CHEN, K.S., LIN, S.L., LIN, Y.C., and CHENG, W.L., 2016. Reducing Pollutant Emissions from a Heavy-Duty Diesel Engine by Using Hydrogen Additions. *Fuel*, 172: 89-95.
- JUNHONG, Z. and JUN, H., 2006. CAE Process to Simulate and Optimise Engine Noise and Vibration. *Mechanical Systems and Signal Processing*, 20: 1400–1409.
- KAIMAL, V. K. and VIJAYABALAN, P. A., 2015. Detailed Study of Combustion Characteristics of a DI Diesel Engine Using Waste Plastic Oil and its Blends. *Energy Conversion and Management*, 105: 951–956.
- KARAGÖZ, Y., GÜLER, I., SANDALCI, T., YÜKSEK, L., and DALKILIC, A.S., 2015b. Effect of hydrogen enrichment on combustion characteristics, emissions and performance of a diesel engine. *International Journal of Hydrogen Energy*, In press: 1–10.
- KARAGÖZ, Y., GÜLER, I., SANDALCI, T., YÜKSEK, L., DALKILIC, A.S., and WONGWISES, S., 2015a. Effects of Hydrogen and Methane Addition on Combustion Characteristics, Emissions, and Performance of a CI Engine. *International Journal of Hydrogen Energy*, In press: 1–13.
- KARAGÖZ, Y., SANDALCI, T., YÜKSEK, L. and DALKILIÇ, A. S., 2015c. Engine Performance and Emission Effects of Diesel Burns Enriched by Hydrogen on Different Engine Loads. *International Journal of Hydrogen Energy*, 40: 6702-6713.

- KELLY, S.G., 2012. Mechanical Vibrations: Theory and Applications. Stamford, USA. 616p.
- KHIARI, K., AWAD, S., LOUBAR, K., TARABET, L., MAHMOUD, R. and TAZEROUT, M., 2016. Experimental Investigation of Pistacia Lentiscus Biodiesel as a Fuel for Direct Injection Diesel Engine. *Energy Conversion and Management*, 108: 392–399.
- KOJIMA, M. and JOHNSON, T., 2006. Biofuels for Transport in Developing Countries: Socioeconomic Considerations. *Energy Sustainable Development*, 10: 59–66.
- KÖSE, H. and CINIVIZ, M., 2013. An Experimental Investigation of Effect on Diesel Engine Performance and Exhaust Emissions of Addition at Dual Fuel Mode of Hydrogen. *Fuel Processing Technology*, 114: 26–34.
- KUMAR, P. and REHMAN, A., 2016 Biodiesel in Homogeneous Charge Compression Ignition (HCCI) Combustion. *Renewable and Sustainable Energy Reviews*, 56: 536–550.
- LESNIK, L. and BILUS, I., 2016. The Effect Of Rapeseed Oil Biodiesel Fuel on Combustion, Performance, and The Emission Formation Process within a Heavy-Duty Diesel Engine. *Energy Conversion And Management*, 109: 140–152.
- LI, L., WANG, J., WANG, Z., and XIAO, J., 2015. Combustion and Emission Characteristics of Diesel Engine Fuelled with Diesel/Biodiesel/Pentanol Fuel Blends. *Fuel*, 156: 211–218.
- LI, W., LIU, Z. and WANG, Z., 2016. Experimental and Theoretical Analysis of the Combustion Process at Low Loads of a Diesel Natural Gas Dual-Fuel Engine. *Energy*, 94: 728–741.
- LIANG Z., and LEE G.C., 2015. Random Vibration: Mechanical, Structural, and Earthquake Engineering Applications. CRC press, Boca Raton, FL, USA 668p.
- LIU, J., YANG, F., WANG, H., OUYANG, M. and HAO, S., 2013. Effects of Pilot Fuel Quantity on the Emissions Characteristics of a CNG/Diesel Dual Fuel Engine with Optimized Pilot Injection Timing. *Applied Energy*, 110: 201–206.

- LIU, X., RANDALL, R. B. and ANTONI, J., 2008. Blind Separation of Internal Combustion Engine Vibration Signals by a Deflation Method. *Mechanical Systems and Signal Processing*, 22: 1082–1091.
- MILLO, F., KUMAR DEBNATH, B., VLACHOS, T., CIARAVINO, C., POSTRIOTI, L., and BUITONI, G., 2015. Effects of Different Biofuels Blends on Performance and Emissions of an Automotive Diesel Engine. *Fuel*, 159: 614–627.
- MOFIJUR, M., RASUL, M.G., HYDE, J., AZAD, A.K., MAMAT, R., and BHUIYA, M.M.K., 2016. Role of Biofuel and Their Binary (Diesel – Biodiesel) and Ternary (Ethanol – Biodiesel – Diesel) Blends on Internal Combustion Engines Emission Reduction. *Renewable and Sustainable Energy Reviews*, 53: 265–278.
- ÖZENER, O., YÜKSEK, L., ERGENÇ, A. T. and ÖZKAN, M., 2014. Effects of Soybean Biodiesel on a DI Diesel Engine Performance, Emission and Combustion Characteristics. *Fuel*, 115: 875–883.
- PALI, H. S., KUMAR, N. and ALHASSAN, Y., 2015. Performance and Emission Characteristics of an Agricultural Diesel Engine Fuelled with Blends of Sal Methyl Esters and Diesel. *Energy Conversion and Management*, 90: 146–153.
- PAPAGIANNAKIS, R. G. and HOUNTALAS, D. T., 2003. Experimental Investigation Concerning the Effect of Natural Gas Percentage on Performance and Emissions of a DI Dual Fuel Diesel Engine. *Applied Thermal Engineering*, 23: 353–365.
- PAPAGIANNAKIS, R. G. and HOUNTALAS, D. T., 2004. Combustion and Exhaust Emission Characteristics of a Dual Fuel Compression Ignition Engine Operated with Pilot Diesel Fuel and Natural Gas. *Energy Conversion and Management*, 45: 2971–2987.
- PAPAGIANNAKIS, R. G., RAKOPOULOS, C. D., HOUNTALAS, D. T. and RAKOPOULOS, D. C., 2010. Emission Characteristics of High Speed, Dual Fuel, Compression Ignition Engine Operating in a Wide Range of Natural Gas/Diesel Fuel Proportions. *Fuel*, 89: 1397–1406.

- PARTHASARATHY, M., ISAAC JOSHUARAMESH LALVANI, J., DHINESH, B. and ANNAMALAI, K., 2015. Effect of Hydrogen on Ethanol–Biodiesel Blend on Performance and Emission Characteristics of a Direct Injection Diesel Engine. *Ecotoxicology and Environmental Safety*, In press: 1–7.
- PAUL, A., PANUA, R. S., DEBROY, D. and BOSE, P. K., 2014. Effect of Compressed Natural Gas Dual Fuel Operation with Diesel and Pongamia Pinnata Methyl Ester (PPME) as Pilot Fuels on Performance and Emission Characteristics of a CI (compression ignition) engine. *Energy*, 68: 495–509.
- PLINT, M., and MARTYR, A., 2001. *Engine Testing Theory and Practice*. Butterworth-Heinemann, Oxford, 350p.
- POOMPIPATPONG, C. and CHEENKACHORN, K. A., 2011. Modified Diesel Engine for Natural Gas Operation: Performance and Emission Tests. *Energy*, 36: 6862–6866.
- QUADRI, S. A. P., MASOOD, M. and RAVI KUMAR, P., 2015. Effect of Pilot Fuel Injection Operating Pressure in Hydrogen Blended Compression Ignition Engine: An Experimental Analysis. *Fuel*, 157: 279–284.
- RAHMAN, S. M. A., MASJUKI, H.H., KALAM, M.A., ABEDIN M.J., SANJID A., and IMTENAN, S., 2014. Effect of Idling on Fuel Consumption and Emissions of a Diesel Engine Fuelled by Jatropha Biodiesel Blends. *J. Clean. Prod.* 69, 208–215.
- RAMIREZ VERDUZCO, L. F., 2013. Density and Viscosity of Biodiesel as a Function of Temperature: Empirical Models. *Renewable and Sustainable Energy Reviews*, 19: 652–665.
- RASHED, M. M., KALAM, M.A., MASJUKI, H.H., MOFIJUR, M., RASUL, M.G. and ZULKIFLI, N.W.M., 2016. Performance and Emission Characteristics of a Diesel Engine Fuelled with Palm, Jatropha, and Moringa Oil Methyl Ester. *Industrial Crops and Products*, 79: 70–76.
- REDEL-MACIAS, M. D., PINZI, S., LEIVA, D., CUBERO-ATIENZA, A. J. and DORADO, M. P., 2012. Air and Noise Pollution of a Diesel Engine Fuelled with Olive Pomace Oil Methyl Ester and Petrodiesel Blends. *Fuel*, 95: 615–621.

- REDEL-MACIAS, M. D., RODRIGUEZ-CANTALEJO, R. D., PINZI, S., CUBERO-ATIENZA, A. J. and DORADO, M. P., 2014. Evaluation of Sound Quality in a Tractor Driver Cabin Based on the Effect of Biodiesel Fatty Acid Composition. *Fuel*, 118: 194–201.
- ROCABRUNO-VALDÉS, C.I., RAMÍREZ-VERDUZCO, L. F. and HERNÁNDEZ, J. A., 2015. Artificial Neural Network Models to Predict Density, Dynamic Viscosity, and Cetane Number of Biodiesel. *Fuel*, 147: 9–17.
- ROY, M. M., WANG, W. and BUJOLD, J., 2013. Biodiesel Production and Comparison of Emissions of a DI Diesel Engine Fuelled by Biodiesel–Diesel and Canola Oil–Diesel Blends at High Idling Operations. *Applied Energy*, 106: 198–208.
- ROY, S., BANERJEE, R., DAS, A. K. and BOSE, P. K., 2014. Development of an ANN Based System Identification Tool to Estimate the Performance-Emission Characteristics of a CRDI Assisted CNG Dual Fuel Diesel Engine. *Journal of Natural Gas Science and Engineering*, 21: 147–158.
- RYU, K., 2013. Effects of Pilot Injection Timing on the Combustion and Emissions Characteristics in a Diesel Engine Using Biodiesel-CNG Dual Fuel. *Applied Energy* 111, 721–730.
- SAKTHIVEL, G., NAGARAJAN, G., ILANKUMARAN, M. and GAIKWAD, A. B., 2014. Comparative Analysis of Performance, Emission and Combustion Parameters of Diesel Engine Fuelled with Ethyl Ester of Fish Oil and its Diesel Blends. *Fuel*, 132: 116–124.
- SELIM, M. Y., 2001. Pressure–Time Characteristics In Diesel Engine Fuelled with Natural Gas. *Renewable Energy*, 22: 473–489.
- SILVA, C., 2007. *Vibration Fundamentals and Practice*. CRC Press, Boca Raton, 1036s.
- SPEIRS, J., McGLADE, C. and SLADE, R., 2015. Uncertainty in the Availability of Natural Resources: Fossil Fuels, Critical Metals and Biomass. *Energy Policy*, 87: 654–664.

- SUKKASI, S., CHOLLACOP, N., ELLIS, W., GRIMLEY, S. and JAI-IN, S., 2010. Challenges and Considerations for Planning Toward Sustainable Biodiesel Development in Developing Countries: Lessons from the Greater Mekong Subregion. *Renewable and Sustainable Energy Reviews*, 14: 3100–3107.
- SZWAJA, S. and GRAB-ROGALINSKI, K., 2009. Hydrogen Combustion in a Compression Ignition Diesel Engine. *International Journal of Hydrogen Energy*, 34: 4413–4421.
- TAGHIZADEH-ALISARAEI, A., GHOBADIAN, B., TAVAKOLI-HASHJIN, T. and MOHTASEBI, S. S., 2012. Vibration Analysis of a Diesel Engine Using Biodiesel and Petrodiesel Fuel Blends. *Fuel*, 102: 414–422.
- TALEBIAN-KIAKALAIEH, A., AMIN, N. A. S. and MAZAHARI, H. A., 2013. Review on Novel Processes of Biodiesel Production From Waste Cooking Oil. *Applied Energy*, 104: 683–710.
- TARABET, L., LOUBAR, K., LOUNICI, M.S., KHIARI, K., BELMRABET, T. and TAZEROUT, M., 2014. Experimental Investigation of DI Diesel Engine Operating with Eucalyptus Biodiesel/Natural Gas Under Dual Fuel Mode. *Fuel*, 133: 129–138.
- TORREGROSA, A. J., BROATCH, A., PLA, B. and MONICO, L. F., 2013. Impact of Fischer–Tropsch and Biodiesel Fuels on Trade-Offs between Pollutant Emissions and Combustion Noise in Diesel Engines. *Biomass and Bioenergy*, 52: 22–33.
- TÜCCAR G., 2011. Biodiesel Production from Microalgae. Ç. U. Department of Mechanical Engineering – MSc Thesis 69p.
- TÜCCAR, G., TOSUN, E., OZGUR, T. and AYDIN, K., 2014a. Diesel Engine Emissions and Performance from Blends of Citrus Sinensis Biodiesel and Diesel Fuel. *Fuel*, 132: 7–11.
- TÜCCAR, G., ÖZGÜR, T., and AYDIN, K., 2014b. Effect of Diesel–Microalgae Biodiesel–Butanol Blends on Performance and Emissions of Diesel Engine. *Fuel*, 132:47–52

- ULUDAMAR E., OZGUR, C., OZGUR T., and AYDIN, K., 2015. Performance and Emissions Characteristics of a Diesel Engine Fuelled with Ethanol Additive in Diesel-Soybean Biodiesel Fuel Blend. *The Journal of MacroTrends in Energy and Sustainability*, 3: 15-23.
- VALLINAYAGAM, R., VEDHARAJ, S., YANG, W.M., LEE, P.S., CHUA, K.J.E., and CHOU, S.K., 2014. Pine oil–biodiesel blends: A Double Biofuel Strategy to Completely Eliminate the Use of Diesel in a Diesel Engine. *Applied Energy*, 130: 466–473.
- VELMURUGAN, K. and SATHIYAGNANAM, A. P., 2015. Impact of Antioxidants on NO_x Emissions from a Mango Seed Biodiesel Powered DI Diesel Engine. *Alexandria Engineering Journal*, In press: 1-8.
- WANG, Z., ZHAO, Z., WANG, D., TAN M., HAN, Y., LIU, Z., and DOU, H., 2016. Impact of Pilot Diesel Ignition Mode on Combustion and Emissions Characteristics of a Diesel/Natural Gas Dual Fuel Heavy-Duty Engine. *Fuel*, 167: 248–256.
- YILMAZ, A.C., 2010. Design and Applications of Hydroxy (HHO) System. Ç. U. Department of Mechanical Engineering – MSc Thesis 76p.
- YILMAZ, A.C., ULUDAMAR, E., and AYDIN, K., 2010. Effect of Hydroxy (HHO) Gas Addition on Performance and Exhaust Emissions in Compression Ignition Engines. *International Journal of Hydrogen Energy*, 35: 11366–11372.
- ZHANG, H., ZHOU, Q., CHANG, F., PAN, H., LIU, Z.F., LI, H., HU, D.Y., and YANG, S., 2015. Production and Fuel Properties of Biodiesel from Firmiana Platanifolia L.F. as a Potential Non-Food Oil Source. *Industrial Crops and Products*, 76: 768–771.
- ZHOU, J. H., CHEUNG, C. S. and LEUNG, C. W., 2013. Combustion, Performance and Emissions of ULSD, PME and B50 Fuelled Multi-cylinder Diesel Engine with Naturally Aspirated Hydrogen. *International Journal of Hydrogen Energy*, 38: 14837–14848.

ZHOU, J. H., CHEUNG, C. S. and LEUNG, C. W., 2014. Combustion, Performance and Emissions of a Diesel Engine with H_2 , CH_4 and H_2-CH_4 addition. International Journal of Hydrogen Energy, 39: 4611–4621.

ZHOU, J. H., CHEUNG, C. S., ZHAO, W. Z. and LEUNG, C. W., 2016. Diesel–Hydrogen Dual-Fuel Combustion and its Impact on Unregulated Gaseous Emissions and Particulate Emissions Under Different Engine Loads and Engine Speeds. Energy, 94: 110–123.





CURRICULUM VITAE

Erinç ULUDAMAR was born on January 29, 1986. After being graduated Adana Gündoğdu College, he attended to Mechanical Engineering Department of Çukurova University. He graduated from Çukurova University as a Mechanical Engineer in 2009. He started his Master of Science education in Mechanical Engineering Department of Çukurova University in 2009 and he had start to Doctor of Philosophy education in the same department. He has been working as a Research Assistant at the Mechanical Engineering Department of Çukurova University since 2010.



APPENDIX



Experimental and regression analysis of noise and vibration of a compression ignition engine fuelled with various biodiesels

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Abstract

Noise and vibration of ignition compression engine is one of the most complicated field to cope with since every mechanism that compose of the engine affect them separately. In this study, effect of various biodiesel on engine noise and vibration has been studied on an unmodified compression ignition engine. Linear and non-linear based regression analysis based models were also developed to predict the relationship between fuel properties and noise-vibration of the engine with excellent agreement. The results revealed that noise and vibration of the engine decreased with increasing biodiesel ratio until pure biodiesel usage and in linear regression analysis, correlation coefficient (R) values were 0.784 and 0.741 for vibration and sound pressure level, correspondingly. In non-linear regression analysis, correlation coefficient (R) values were 0.814 and 0.777 for vibration and sound pressure level, correspondingly. In linear regression analysis, mean absolute percentage error (MAPE) values were 0.747% and 0.126% for vibration and sound pressure level, correspondingly. In non-linear regression analysis, mean absolute percentage error (MAPE) values were 0.682% and 0.342% for vibration and sound pressure level, respectively.

Keywords

Biodiesel

Compression ignition engine

Engine vibration

Regression analysis

Sound pressure level

1. Introduction

Vehicle comfort is a crucial point to satisfy customers. Automotive manufacturers have to develop their product due to high competition in sector and costumer demands [1-2]. On the other hand, in last decades alternative fuels have become popular due to environmental concerns and emission legislations of the countries [3-4]. Therefore effect of them on engine is undeniable. Biodiesel (fatty acid methyl esters) that derived from vegetable oil or animal fat, is one of the most popular alternative fuels basically due to its advantages such as, renewable, non-toxic, biodegradable and also it is able to use with little or no engine modifications [5-7].

In previous studies, it has been widely reported that by using various biodiesels leads to reduce of carbon monoxide (CO), hydrocarbon (HC) and particulate matter [8-11]. However researchers were also reported higher NO_x emissions for biodiesel compared to diesel fuel [12-14].

In literature although there have been many studies about performance and emission characteristic of biodiesel from various feedstocks, few number of reports have been evaluated its acoustic and vibration characteristics. Taghizadeh-Alisaraei et al., (2012) studied on a six cylinder diesel engine when the engine fuelled with biodiesel blends to observe its effect on engine vibration [15]. How et al., (2014) investigated vibration, performance and emission characteristic of a diesel engine that fuelled with coconut biodiesel blends [16]. Redel-Macías et al. (2012) fuelled a diesel engine with olive pomace oil methyl ester whereas Elshaib et al. (2014) used waste cooking oil up to pure biodiesel to investigate noise changes of diesel engines [17-18]. Siavash et al. (2015) also analysed the noise parameter of a diesel engine for various diesel and biodiesel blends [19].

Engine testing procedure is time consuming and costly processes. In this respect, linear and non-linear regression analysis can be applied to experimental data in order to predict engine output parameters. Levis et al., (2015) used multiple linear regression to assess the relationships between engine activity variables and fuel use and emissions rates [20]. Wongchai et al., (2013) applied the regression analysis to find the relations between hydrogen percentage and the engine vibration. The results for all cases found that the relation between the Average Peak Acceleration (APA) and hydrogen percentage (%H₂) can predict by using linear equation with average coefficient of determination (R^2) = 0.8973 or 2nd polynomial equation with R^2 = 0.9592 [21]. Hirano et al., (2000) described a method for estimating the contributions of engine noise components using multiple regression analysis. With this method, the engine noise level is regarded as a criterion variable and the cylinder pressure level and several parameters are examined as explanatory variables. The accuracy of this method has been confirmed by comparing the results with experimental data [22].

In literature, although it has been many studies about performance and exhaust emission characteristic of internal combustion engines operated with alternative fuels, there is deficiency about their noise and vibration characteristics which are crucial issue for passenger comfort. With the usage of equations obtained from regression analysis, estimation of engine characteristic fuelled with various biodiesels can be possible without time consuming and costly experimental works.

Therefore, in this study, noise and vibration characteristic of a direct ignition engine which was fuelled with low sulphur diesel, sunflower, canola, corn biodiesels and their blends were investigated at different engine speeds. Then linear and non-linear based regression analysis models were developed to predict the relationship between fuel properties and noise-vibration of the engine with excellent agreement.

2. Material and Method

Through this study, experiments were conducted in Petroleum Research and Automotive Engineering Laboratories of the Department of Automotive Engineering at Cukurova University. The methodology involves fuel properties, engine properties, data acquisition equipment, and calculations for post processing.

2.1. Test fuels

In this study, sunflower, canola and corn oil were used as raw materials for biodiesel production since they are easily available in local oil companies in Turkey.

Biodiesel samples were produced via the transesterification reaction. In this reaction, methanol and sodium hydroxide were used as reactant and catalyst. The mixture was heated up to 60°C and kept at this temperature for 90 minutes by stirring. After the reaction period, the crude methyl ester was waited at separating funnel for 8 hours. And then, crude glycerine was separated from methyl ester. Finally, the crude methyl ester was washed by warm water until the washed water became clear and then it dried at 110 °C for 1 hour. Finally washed and dried methyl ester was passed through a filter. Steps of biodiesel production are also briefly illustrated in Fig. 1.

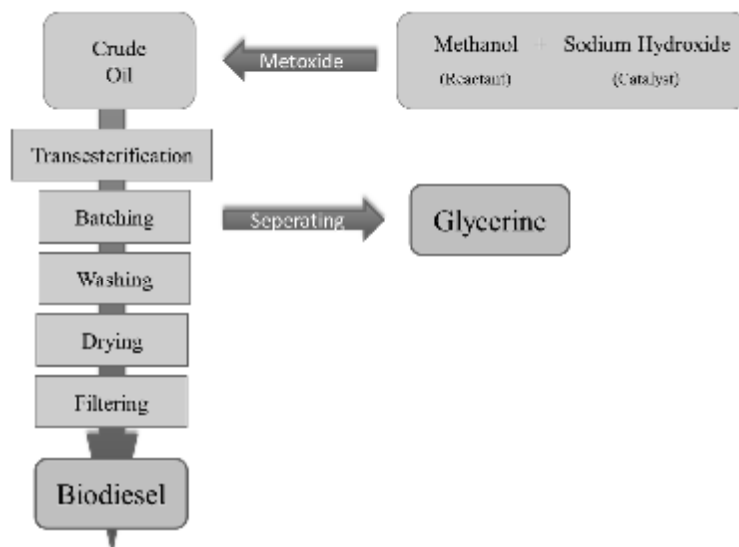


Fig. 1. Biodiesel production steps

Fuel properties were analysed by; Zeltex ZX 440 NIR petroleum analyzer with an accuracy of ± 0.5 for determining cetane number; Tanaka AKV 202 auto

kinematic viscosity test for determining the viscosity; Kyoto electronics DA-130 for density measurement and IKA-Werke C2000 Bomb Calorimeter for gross heating value determination. Tanaka AFP-102 for cold filter plugging point; Tanaka APM-7 Automated Pensky-Martens Closed Cup Flash Point Tester for flash point determination.

Tests fuels were prepared as pure low sulphur diesel (D100), 80% diesel, 20% sunflower biodiesel (SB20); 60% diesel, 40% sunflower biodiesel (SB40); 40% diesel, 60% sunflower biodiesel (SB60); 20% diesel, 80% sunflower biodiesel (SB80); 80% diesel, 20% canola biodiesel (CaB20); 60% diesel, 40% canola biodiesel (CaB40); 40% diesel, 60% canola biodiesel (CaB60); 20% diesel, 80% canola biodiesel (CaB80); 80% diesel, 20% corn biodiesel (CoB20); 60% diesel, 40% corn biodiesel (CoB40); 40% diesel, 60% corn biodiesel (CoB60); 20% diesel, 80% corn biodiesel (CoB80), by volume and pure sunflower (SB100), canola (CaB100), and corn (CoB100) biodiesels were also used for engine tests.

2.2. Experimental Engine

In this work, experiments were performed on a four stroke, four cylinder, and direct injection diesel engine. Experimental layout is shown in Fig. 2 and engine specifications are given in Table 1.

The engine was warmed up to constant operating temperature and engine fuel line was cleaned before introduce with other fuel and waited until the engine became stable and then experimental data were gathered. Fuels were tested at 1200, 1500, 1800, 2100, and 2400 rpm engine speeds under no load condition.

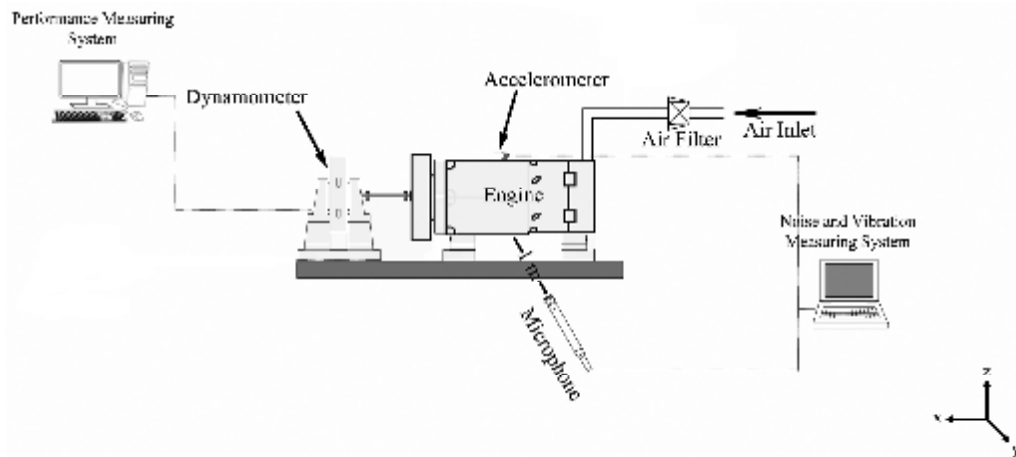


Fig. 2. Experimental layout.

Table 1

Technical specifications of the test engine.

Brand	Mitsubishi Canter
Model	4D34-2A
Configuration	In line 4
Firing order	1-3-4-2
Type	Direct injection diesel with glow plug
Displacement	3907 cc
Bore	104 mm
Stroke	115 mm
Power	89 kW @ 3200 rpm
Torque	295 Nm @ 1800 rpm
Oil cooler	Water cooled
Weight	325 kg

2.3. Measuring System, Accelerometer and Microphone

Acoustic and vibration data were recorded via Soundbook™ universal portable measuring system with SAMURAI v2.6 software from SINUS Messtechnik GmbH. It is capable to double integration of the time signal as filtering according to ISO 10816, ISO 7919 and ISO 2954 standards and sound level meter (SLM) of the software meets the Class 1 SLM according to IEC 60651, IEC 60804, DIN EN 61672-1:2003 standards allowing simultaneous measurements with the frequency weightings A, C, Z.

Triaxial ICP® accelerometer with 1.02 mV/(m/s²) sensitivity and ± 4905 m/s² measurement range was adhered on engine block with quick bonding gels to measure the vibration even in high frequency range. Data were collected in three orthogonal of the test engine. Sound pressure level of the engine was measured by using a GRAS half-inch free-field standard microphone set which has 50 mV/Pa sensitivity, 3.15 Hz to 20 kHz frequency range and 17 dB(A) to 149 dB dynamic range. The microphone was placed at 1 m distance from the block surface.

Time and frequency domains were analysed in x (longitudinal), y (lateral) and z (vertical) axes. Since RMS (root mean square) value is the most relevant measure of vibration level (it gives an amplitude value by considering time history of the wave), the results were described as RMS value. Formula that was used to calculate RMS value was presented in eq. (1). a_w (m/s²) represents the weighted acceleration and T represents measurement time.

$$a_w = \sqrt{\frac{1}{T} \int_0^T a_w^2(t) dt} \quad (1)$$

Total vibration acceleration (a_{total}) is the value to show combined acceleration of vertical (a_x), lateral (a_y) and longitudinal (a_z). It was calculated by the formula given in eq. (2).

$$a_{total} = \sqrt{a_x^2 + a_y^2 + a_z^2} \quad (2)$$

2.4. Linear and Non-Linear Regression Analysis

Before performing the analysis, correlation coefficients between all parameters were identified by using “corrcoef” command in MATLAB. Parameters which were selected as input in order to estimate outputs should be determined according to correlation coefficients between them. Therefore, all proper predictors which have higher correlation coefficients were selected to define each of predicted values. Since density, cetane number, kinematic viscosity, and gross heating value have strongly affected combustion characteristics which directly related to noise and vibration of a compression ignition engine, these parameters were selected as input for estimation.

One of the most widely used method to relate dependent variable(s) with independent variable(s) is regression analysis. It is a statistical process to find functional relationship between variables. Regression analysis is mostly used for prediction.

In linear regression, the function is linear equation and dependent variable can be expressed as a function of independent variable(s) in form of [23]:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_n X_n \quad (3)$$

In non-linear regression, the function is non-linear equation and dependent variable can be expressed as a function of independent variable(s) in form of [23]:

$$Y = a_0 (X_1^{a_1}) (X_2^{a_2}) \dots (X_n^{a_n}) \quad (4)$$

Where Y is dependent variable, β_0 to β_n and a_0 to a_n are equation parameters and X_1 to X_n are independent variables.

3. Result and Discussion

3.1. Fuel properties

Quality measurements of test fuels were performed according to TS EN 14214 biodiesel standard and EN 590 diesel standard. Fuel properties are given in Table 2.

Table 2

Fuel Properties of the test fuels.

Test Fuels	Density (kg/l)	Cetane Number	Kinematic Viscosity at 40°C (mm ² /s)	Gross Heating Value (kJ/kg)	Flash point (°C)
D100	0,837	59,3	2,7	45857	74,5
SB20	0,844	56,5	3,1	44246	101,5
SB40	0,854	53,6	3,4	43430	106,5
SB60	0,869	51,1	3,7	42998	
SB80	0,876	49,0	4,1	41874	
SB100	0,886	44,5	4,5	39149	>140
CaB20	0,846	56,9	3,2	43413	76,7
CaB40	0,857	54	3,5	42986	83,9
CaB60	0,861	51,8	3,8	41568	
CaB80	0,869	50	4,0	39974	
CaB100	0,883	46	4,7	38363	120,5
CoB20	0,847	55,4	3	42266	85,5
CoB40	0,856	52,1	3,2	41881	91,5
CoB60	0,862	48,9	3,5	39368	
CoB80	0,870	45	3,8	38158	
CoB100	0,887	42,2	4,2	37476	>140
EN590	0,820–0,845	Min 51	2.0–4.5	-	Min 55
ASTM D 6751	-	Min 47	1.9–6.0	-	Min 93
EN 14214	0,860 – 0,900	Min 51	3,5 – 5,0	-	Min 120

3.2. Vibration of the engine

For each experiment, vibration data gathered from the engine block with 51,2 kHz sampling frequency for 12 seconds.

Vibration acceleration spectrum characteristic of CaB100@1500 rpm and CoB20@2400 rpm are presented in Figs. 3 and 4, respectively as examples. First columns of the figures belong to data of x- axis, second columns represent y- axis and the last columns represent z- axis. Spectrum of the test engine may also characterize by a wide resonance zone and overlapped on worn auxiliary equipment which has different kinds of clearances [24].

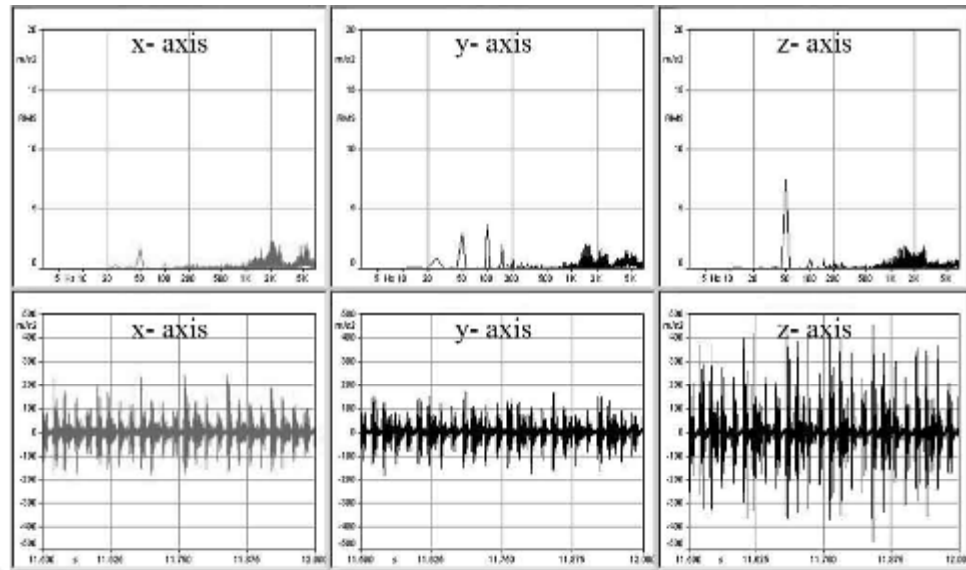


Fig. 3. Time and frequency domain signal of the engine that fuelled with SB20 at 1500 rpm

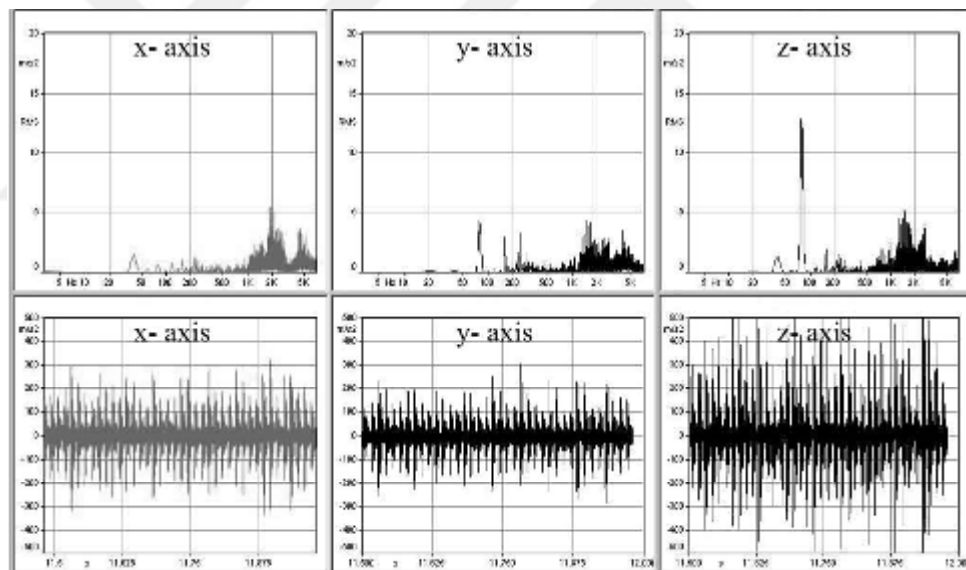


Fig. 4. Time and frequency domain signal of the engine that fuelled with CoB100 at 2400 rpm

Fig. 5, 6 and 7 illustrate the vibration of the engine block from 1200 rpm to 2400 rpm. Since upward and downward piston movement is the primarily engine vibration source, the dominant frequency was found as the twice of the engine operating speed. Furthermore, other parameters such as burning pressure, input from the timing gear system, fittings of the engine, inputs transmitted from the motor body, flow of cooling factor, inlet and outlet gases, inlet and outlet of fuel through injector, inertia of cam unit's parts, impacts of head's parts may affect engine vibration [25-26].

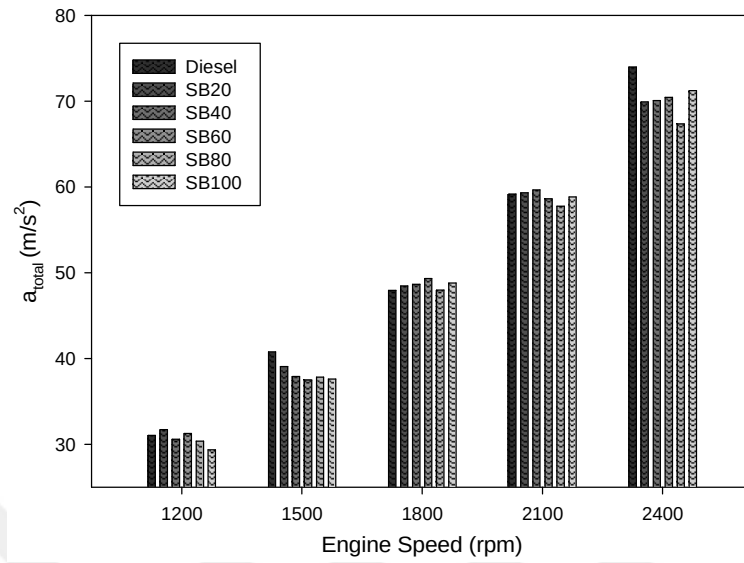


Fig 5. a_{total} versus engine speed when the engine fuelled with sunflower biodiesel

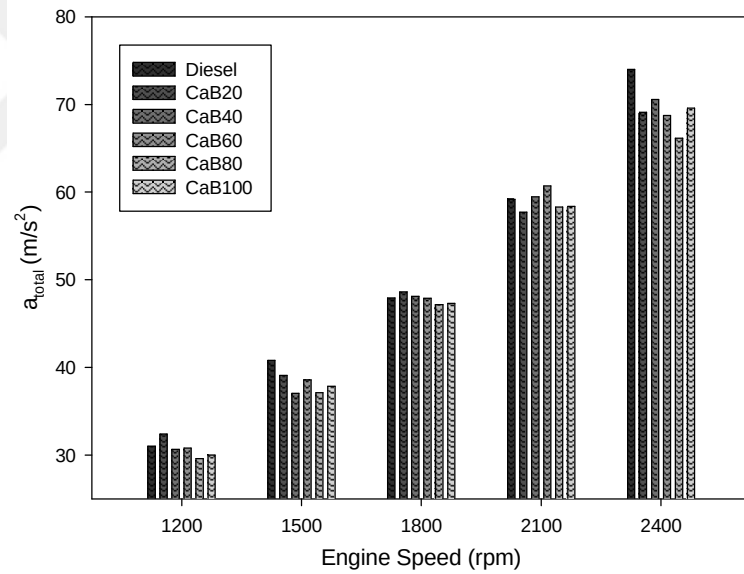


Fig 6. a_{total} versus engine speed when the engine fuelled with canola biodiesel

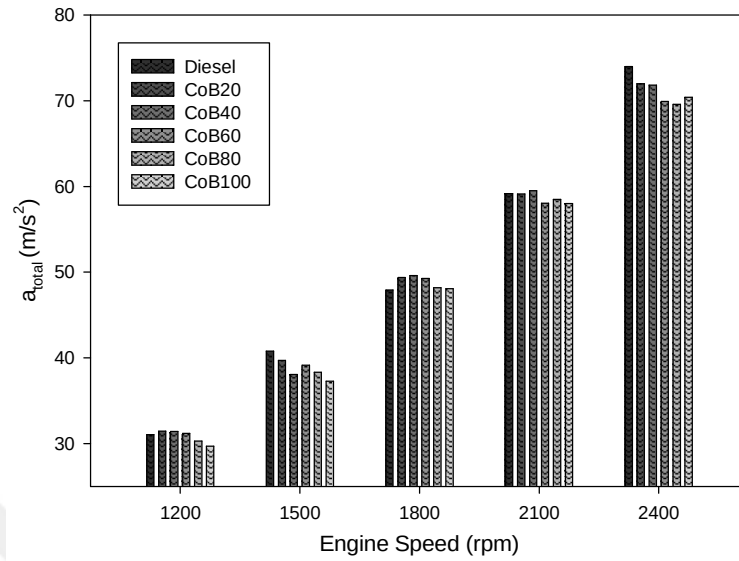


Fig 7. a_{total} versus engine speed when the engine fuelled with corn biodiesel

It is noticed that the values of a_{total} increased with the increase of engine speed due to the increment of inertia forces such as crank rotation speed. The average of engine vibration (a_{total}) decreased by 1,72%, 2,37%, 0,5% for SB20, CaB20, CoB20; 2,38%, 2,79%, 0,98% for SB40, CaB40, CoB40; 2,28%, 2,44%, 2,11% for SB60, CaB60, CoB60; 4,60%, 5,76%, 3,19% for SB80, CaB80, CoB80 and 2,80%, 3,87%, 3,72% for SB100, CaB100, CoB100, respectively when compared with D100. Variations in fuel properties may explain the differences.

Since biodiesel contains extra oxygen, combustion quality of biodiesel is better than combustion of conventional diesel fuel. That's why; many researchers have concluded on that, oxides of nitrogen exhaust emission generally increases with biodiesel addition by the same reason [12-14]. Enhancement of combustion with the usage of biodiesel means lowering vibration of the diesel engine block.

3.3. Sound pressure level of the engine

Experiments were conducted in a sound insulated room. Furthermore, periphery of dynamometer was covered by a wooden box with sound absorber panels.

A- weighted sound pressure level, which is similar to perceived by the human ear was used in order to processing of results. In Figs. 8, 9, and 10, the results of noise measurement with diesel and biodiesel blend fuels are shown.

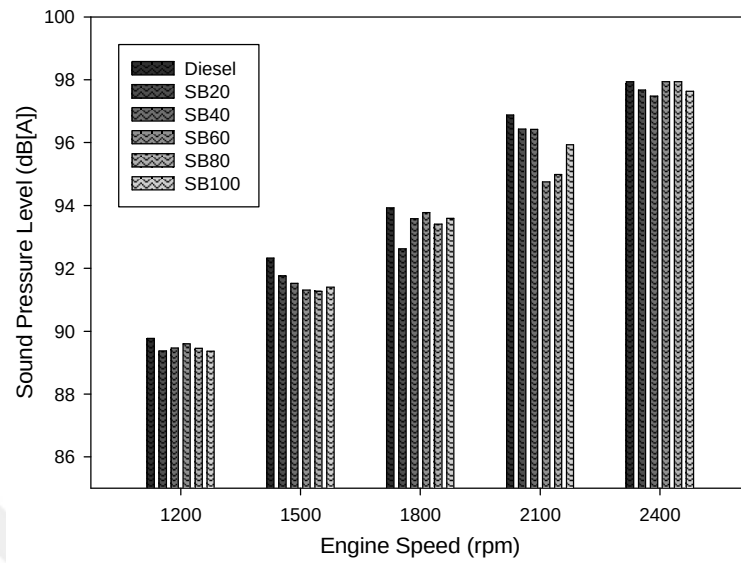


Fig 8. Sound pressure level versus engine speed when the engine fuelled with sunflower biodiesel

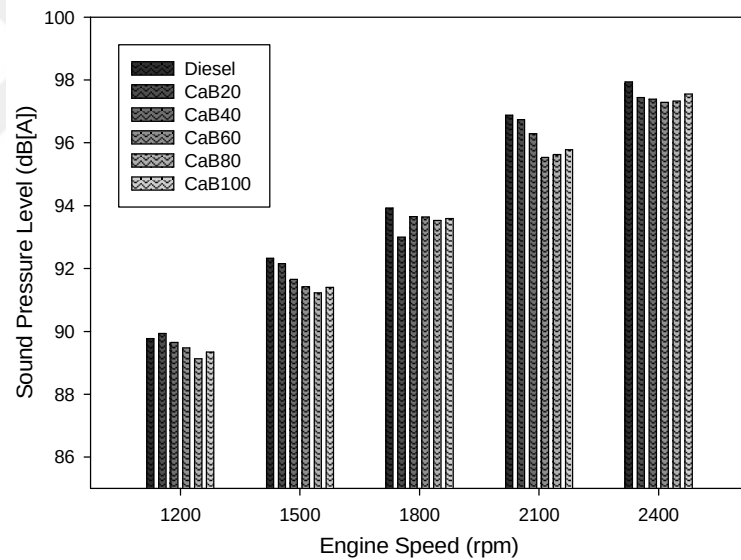


Fig 9. Sound pressure level versus engine speed when the engine fuelled with canola biodiesel

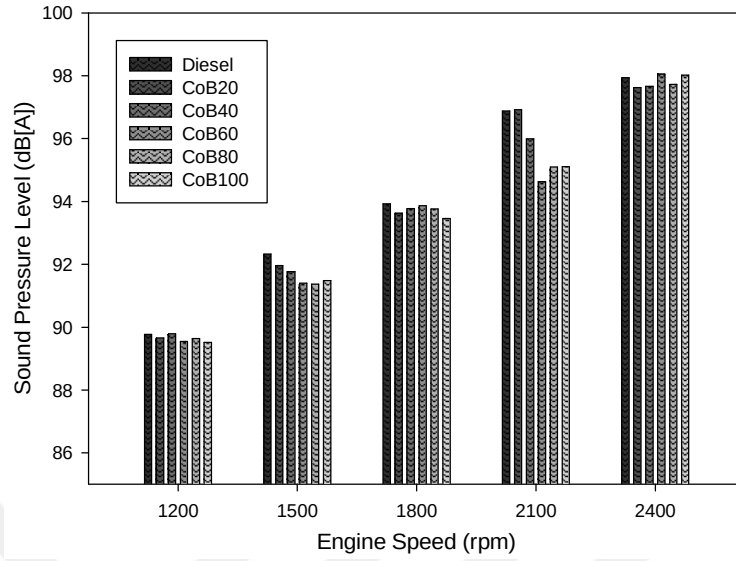


Fig 10. Sound pressure level versus engine speed when the engine fuelled with corn biodiesel

Sound pressure level of the engine was also increased by increasing engine speed. Average sound pressure level found slightly lower than that of low sulphur diesel fuel with 0,6 dB[A], 0,3 dB[A], 0,2 dB[A], for SB20, CaB20, CoB20; 0,5 dB[A], 0,4 dB[A], 0,4 dB[A], for SB40, CaB40, CoB40; 0,7 dB[A], 0,7 dB[A], 0,7 dB[A], for SB60, CaB60, CoB60; 0,8 dB[A], 0,8 dB[A], 0,7 dB[A], for SB80, CaB80, CoB80; and 0,6 dB[A], 0,6 dB[A], 0,7 dB[A], for SB100, CaB100, CoB100, respectively. Decrement of sound pressure level may be related with the decrement of engine vibration.

3.4. Results of Linear and Non-Linear Regression Analysis

In this study, both linear and non-linear regression analyses were applied to experimental data.

Forecasted parameters are vibration and sound pressure level of the internal combustion engine. Density, cetane number, viscosity and lower heating value are selected as input parameters to predict vibration and sound pressure level of engine.

SPSS which is a software package used for statistical analysis was used to perform regression analysis. Results of analysis can be seen from the following equations (5, 6, 7, and 8):

$$\text{Vibration} = 71.126 - (19.43 * \text{density}) - (0.123 * \text{CN}) - (1.042 * \text{viscosity}) + (0.000121 * \text{LHV}) \quad (5)$$

$$\text{Sound Level} = 85.097 + (10.596 * \text{density}) + (0.041 * \text{CN}) - (0,366 * \text{viscosity}) - (3.266 * 10^{-5} * \text{LHV}) \quad (6)$$

$$\text{Vibration} = 35.318 * (\text{density}^{0.003}) * (\text{CN}^{-0.101}) * (\text{viscosity}^{-0.109}) * (\text{LHV}^{0.082}) \quad (7)$$

$$Sound\ Level = 103.276 * (density^{0.127}) * (CN^{0.017}) * (viscosity^{-0.02}) * (LHV^{-0.011}) \quad (8)$$

Equation 5 and 6 linearly calculates vibration and sound pressure level of engine when we put the input parameters into equation. On the other hand, equation 7 and 8 non-linearly calculates vibration and sound pressure level of engine when we put the input parameters into equation.

The results of analysis can be seen from the following Figs. 11 and 12. As seen from figure there is good agreement between actual and predicted data. Correlation Coefficient (R) and mean absolute percentage error (MAPE) were selected as performance parameter and results are given in the following Table 3:

Table 3

Performance comparison of linear and non-linear regression.

It can be concluded that, vibration and sound pressure level can be predicted with an acceptable accuracy with the usage of linear and non-linear regression.

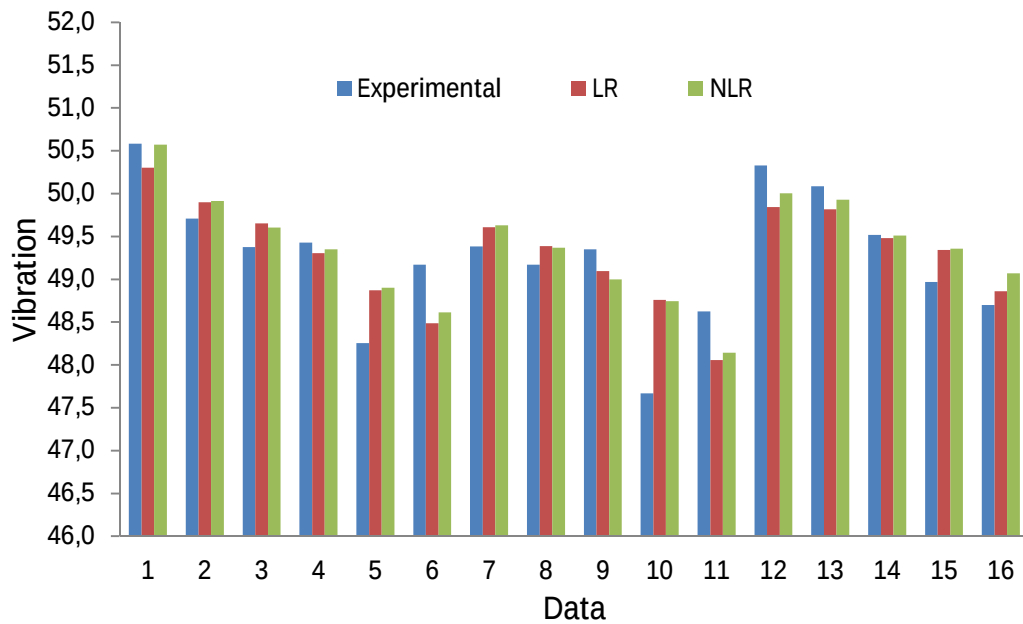


Fig 11. Comparison of actual and predicted vibration data

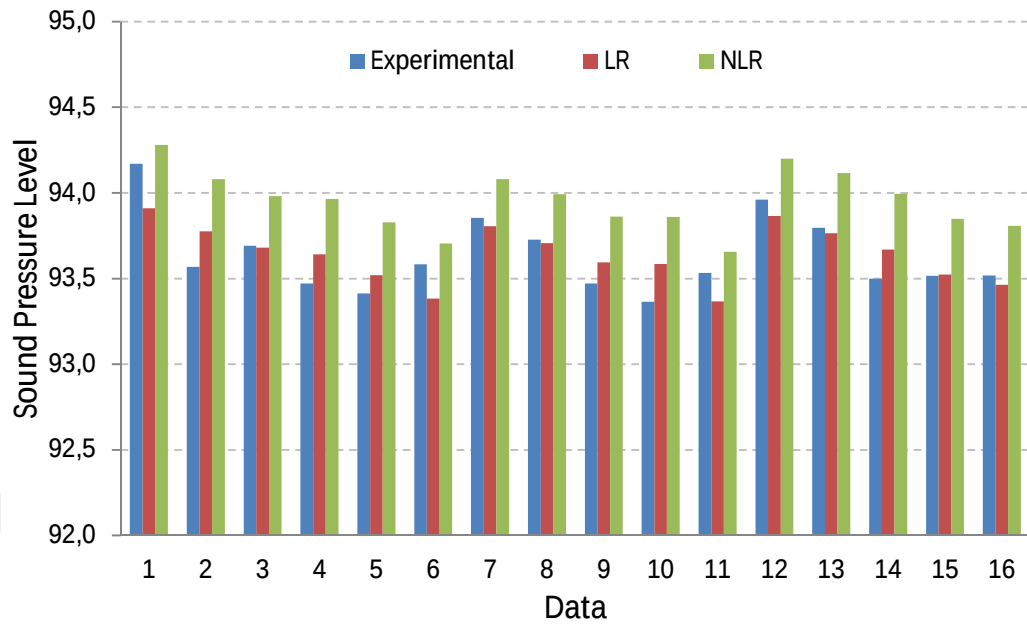


Fig 12. Comparison of actual and predicted sound pressure level data

4. Conclusion

The objective of this study was to investigate the effect of biodiesel fuels on an unmodified compression ignition engine with regard to noise and vibration. Throughout the experiments the engine fuelled with low sulphur diesel, sunflower biodiesel, canola biodiesel, and corn biodiesel blends. Furthermore, both linear and non-linear regression analysis were applied to experimental data in order to predict vibration and sound pressure level of engine.

According to experiments and results, following summarizes were brought out:

- Sound pressure level and vibration acceleration of the test engine increased with engine speed,
- Averagely, compared to low sulphur diesel fuel, vibration and sound pressure level decrement was observed with biodiesel usage,
- The dominant frequency was regardless of fuel type. It significantly affected by engine speed due to upward and downward piston movement,
- Regression analysis was used to experimental data,
- Vibration and sound pressure level can be predicted with an acceptable accuracy with the usage of linear and non-linear regression.

References

- [1] Atalay M, Anafarta N, Sarvan F. The Relationship between Innovation and Firm Performance: An Empirical Evidence from Turkish Automotive Supplier Industry. *Procedia - Soc Behav Sci* 2013;75:226–35.
- [2] Holm M, Garcia AC, Adamson G, Wang L. Adaptive Decision Support for Shop-floor Operators in Automotive Industry. *Procedia CIRP* 2014;17:440–5.
- [3] Ganapathy T, Gakkhar RP, Murugesan K. Influence of injection timing on performance, combustion and emission characteristics of *Jatropha* biodiesel engine. *Appl Energy* 2011.
- [4] Ong HC, Mahlia TMI, Masjuki HH, Honnery D. Life cycle cost and sensitivity analysis of palm biodiesel production. *Fuel* 2012;98:131–9.
- [5] Alptekin E, Canakci M, Ozsezen AN, Turkcan A, Sanli H. Using waste animal fat based biodiesels–bioethanol–diesel fuel blends in a DI diesel engine. *Fuel* 2015;157:245–54.
- [6] Arbab MI, Masjuki HH, Varman M, Kalam MA., Imtenan S, Sajjad H. Fuel properties, engine performance and emission characteristic of common biodiesels as a renewable and sustainable source of fuel. *Renew Sustain Energy Rev* 2013;22:133–47.
- [7] Zhang H, Zhou Q, Chang F, Pan H, Liu X-F, Li H, et al. Production and fuel properties of biodiesel from *Firmiana platanifolia* L.f. as a potential non-food oil source. *Ind Crops Prod* 2015;76:768–71.
- [8] Nantha Gopal K, Thundil Karupparaj R. Effect of *Pongamia* Biodiesel on Emission and Combustion Characteristics of DI Compression Ignition Engine. *Ain Shams Eng J* 2015;6:297–305.
- [9] Mohsin R, Majid ZA, Shihnan AH, Nasri NS, Sharer Z. Effect of Biodiesel Blends on Engine Performance and Exhaust Emission for Diesel Dual Fuel Engine. *Energy Convers Manag* 2014;88:821–28.
- [10] Cheung CS, Man XJ, Fong KW, Tsang OK. Effect of Waste Cooking Oil Biodiesel on the Emissions of a Diesel Engine. *Energy Procedia* 2015;66:93–6.
- [11] Habibullah M, Masjuki HH, Kalam MA, Rizwanul Fattah IM, Ashraful AM, Mobarak HM. Biodiesel Production and Performance Evaluation of Coconut, Palm and Their Combined Blend with Diesel in a Single-Cylinder Diesel Engine. *Energy Convers Manag* 2014;87:250–7.
- [12] Tüccar G, Tosun E, Özgür T, Aydın K. Diesel engine emissions and performance from blends of citrus sinensis biodiesel and diesel fuel. *Fuel* 2014;132:7–11.
- [13] Özener O, Yüksek L, Ergenç AT, Özkan M. Effects of soybean biodiesel on a DI diesel engine performance, emission and combustion characteristics. *Fuel* 2014;115:875–83.
- [14] Sayin C, Gumus M, Canakci M. Influence of injector hole number on the performance and emissions of a DI diesel engine fuelled with biodiesel–diesel fuel blends. *Appl Therm Eng* 2013;61:121–8.
- [15] Taghizadeh-Alisaraei A, Ghobadian B, Tavakoli-Hashjin T, Mohtasebi SS. Vibration analysis of a diesel engine using biodiesel and petrodiesel fuel

- blends. *Fuel* 2012;102:414–22.
- [16] How HG, Masjuki HH, Kalam MA, Teoh YH. An investigation of the engine performance, emissions and combustion characteristics of coconut biodiesel in a high-pressure common-rail diesel engine. *Energy* 2014;69:749–59.
 - [17] M.D. Redel-Macías, S. Pinzi, D. Leiva, A. J. Cubero-Atienza, M.P. Dorado, Air and noise pollution of a diesel engine fuelled with olive pomace oil methyl ester and petrodiesel blends, *Fuel*. 95 (2012) 615–21.
 - [18] Elshaib AA, Kamal MM, Elahwany AA. Performance of a diesel engine fuelled by waste cooking oil biodiesel. *J Energy Inst* 2014;87:11–7.
 - [19] Siavash NK, Najafi G, Hasanbeigi R, Ghobadian B. Acoustic Analysis of a Single Cylinder Diesel Engine Using Biodiesel Fuel Blends. *Energy Procedia* 2015;75:893–9.
 - [20] Lewis P, Fitriani H, Arocho I. Engine Variable Impact Analysis of Fuel Use and Emissions for Heavy-Duty Diesel Maintenance Equipment. *Transportation Research Record: Journal of the Transportation Research Board* 2015;2482:8–15.
 - [21] Wongchai B, Visuwan P, Chuepeng S. The Vibration Analysis of Diesel Engine with Hydrogen-Diesel Dual Fuel. *American Journal of Applied Sciences* 2013; 10:8-14.
 - [22] Hirano I, Kondo M, Uraki Y, Asahara Y. Using multiple regression analysis to estimate the contributions of engine-radiated noise components. *JSAE Rev* 1999;20:363–8.
 - [23] Bilgili M, Sahin B. Comparative analysis of regression and artificial neural network models for wind speed prediction. *Meteorol Atmos Phys* 2010;109:61–72.
 - [24] Dabrowski Z, Komorska I, Identification of engine vibroacoustic model for diagnostics of mechanical defects. *Proceedings of PACAM XII* 2012;2–6.
 - [25] Czech P, Lazarz B, Madej H, Wojnar G, Vibration Diagnosis of Car Motor Engines. *Acta Technica Corviniensis* 2010;3:37–42.
 - [26] Tomaszewski F, Szymański G, Frequency Analysis of Vibrations of the Internal Combustion Engine Components in the Diagnosis of Engine Processes. *Arch. Transp* 2012;24:117–125.

Vibration, noise and exhaust emissions analyses of an unmodified compression ignition engine fuelled with low sulphur diesel and biodiesel blends with hydrogen addition

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Abstract

Depletion thread of fossil fuels and emission regularities of countries enforce researchers to use alternative resources in diesel engines. Hydrogen and biodiesel are one of the most important alternative fuels. Therefore, all effect of them must be investigated on diesel engine. In this study, experimental investigation was conducted on an unmodified four-stroke four-cylinder diesel engine, in order to comprehend its noise and vibration characteristics when the engine was fuelled with sunflower, canola, and corn biodiesel blends with %20 and %40 volume ratio while H₂ injected through inlet manifold with 3 l/min and 6 l/min flow rates. The results revealed that changes of sound pressure level with H₂ addition depended on engine speed whereas vibration acceleration was decreased with addition of gas at all engine speeds. Furthermore, in this paper exhaust emission characteristic of the engine when it was fuelled with sunflower, canola and corn, biodiesel blends and H₂ gas addition was presented.

Keywords: Noise, Vibration, Exhaust emission, Hydrogen, Biodiesel

Introduction

Compression ignition (CI) engine that is widely used for power generation in transportation and heavy industrial is the most popular engine type since invention of them, principally, due to its advantages of high thermal efficiency and durability [1-6]. Although compression ignition engines mostly still rely on conventional diesel fuel, there are many researches about alternative fuels since the thread of depletion of fossil-based fuels and emission regulations in many countries [7-11]. Therefore, cleaner and sustainable fuels have been gained prominence in recent years [12-13]. Biodiesel (fatty acid methyl esters) that derived from vegetable oil or animal fat is one of the promising alternative fuel to use in compression ignition engines [14-15]. It can be used in compression ignition engines directly or with little modification [16-18]. Improving effect on exhaust emissions such as carbon monoxide (CO), hydrocarbon (HC), sulphur dioxide (SO₂) is another important advantage of using biodiesel [19-23]. However increment of NO_x emissions is the primary drawback of using it [24-27].

Hydrogen (H₂) is another renewable alternative fuel. Performance and/or emission characteristics of compression ignition engines with H₂ addition has been studied by many researchers. On the studies, H₂ were mostly used with other fuel types due to high auto-ignition temperature of H₂ [28-29]. It has been reported by many researchers that carbon dioxide (CO₂), CO and HC emissions were reduced, whereas NO_x emissions increased with H₂ addition. On the other hand decrement at engine performance was also observed by researchers [30-31].

Noise and vibration characteristic of internal combustion engines with different fuels were also investigated by some researchers. How et al. (2014) investigated the effect of coconut biodiesel on engine vibration characteristic [32]. Nguyen and Mikami, (2013) studied combustion noise characteristic with addition of H₂ into intake air of a compression ignition engine [33]. Taghizadeh-Alisaraei et al., (2012) evaluated vibration characteristic of a compression ignition engine which is fuelled with diesel-biodiesel blend [34]. Gravalos et al., (2013) blended methanol and ethanol with gasoline in order to investigate vibration behaviour of a spark ignition engine and Redel-Macias et al., (2014) evaluated the sound quality inside a tractor cabin when their engine was fuelled with biodiesel-diesel blend [35-36].

Internal combustion engine is a significant source of noise and vibration in a vehicle thereby, considerable attention should be paid on them. Although in literature there are so many studies about performance and emission characteristic of H₂ addition, there is a gap about its noise and vibration effect on compression ignition engine. In this study, sound pressure level, vibration and exhaust emission characteristic of an unmodified compression ignition engine has been evaluated. Throughout the experiments, the engine was fuelled with sunflower, canola, and corn biodiesel blends with low sulphur diesel fuel. Furthermore H₂ at different flow rates was added into intake air.

Material and Method

In this study, experiments were conducted in Petroleum Research and Automotive Engineering Laboratories of Automotive Engineering Department at Cukurova University.

Sunflower, canola, and corn biodiesels were prepared via transesterification reaction by using 6:1 methanol to oil molar ratio as reactant and 0.5% (by weight of oil) sodium hydroxide as catalyst. Before transesterification reaction, methanol and sodium hydroxide were mixed in order to obtain methoxide while the oil was heated up to 60 °C. After the oil and methoxide were blended, the mixture kept at this temperature for 90 minutes by stirring. At the end of transesterification, the crude methyl ester was waited at separating funnel for 8 hours. And then, crude glycerine was separated from methyl ester. The crude methyl ester was washed by warm water until the washed water became clear and then it dried at 110 °C for 1 hour. Finally, washed and dried methyl ester was passed through a filter.

Blends were prepared by volume ratio of 20% and 40% for each biodiesel with low sulphur diesel fuel. Properties of test fuels and pure biodiesel fuels were analysed by Zeltex ZX 440 NIR petroleum analyzer for determining cetane number; Tanaka AKV-202 auto kinematic viscosity test for determining the viscosity; Kyoto electronics DA-130 for density measurement; IKA-Werke C2000 Bomb Calorimeter for lower heating value measurement and Tanaka APM-7 Automated Pensky-Martens Closed Cup Flash Point Tester was used for flash point determination.

Experiments were conducted on a four stroke, four cylinder, and direct injection Mitsubishi Canter diesel engine. Throughout the experiments test engine was fuelled with low sulphur diesel (D100), 20% and 40% sunflower biodiesel – low sulphur diesel fuel blend (SB20 and SB40, respectively) 20% and 40% canola biodiesel – low sulphur diesel fuel blend (CaB20 and CaB40, respectively), 20% and 40% corn biodiesel – low sulphur diesel fuel blend (CoB20 and CoB40, respectively), while the hydrogen was added into the intake manifold with various flow rates of 3 l/min and 6 l/min (H3 and H6, respectively). The energy substitution ratio of H₂ was calculated according to eq. 1 and in table 1, the energy substitution ratio of hydrogen with diesel-biodiesel blends was given.

$$H_2 \text{ energy substitution ratio} = \frac{\dot{m}_{H_2} * LHV_{H_2}}{\dot{m}_{fuel} * LHV_{fuel} + \dot{m}_{H_2} * LHV_{H_2}} \quad (1)$$

Where;

$\dot{m}_{H_2}$ = the mass flow rate of H₂

$\dot{m}_{fuel}$ = the mass flow rate of fuel blends

LHV= lower heating value

Table 1H₂ energy substitution ratio.

Fuel Type	Engine speed (rpm)	H3 (%)	H6 (%)
D100	1200	4,36	8,36
	1500	3,03	5,89
	1800	2,10	4,12
	2100	1,66	3,26
	2400	1,54	3,03
SB20	1200	3,66	7,07
	1500	3,11	6,04
	1800	2,20	4,30
	2100	1,92	3,77
	2400	1,58	3,11
SB40	1200	3,51	6,78
	1500	2,94	5,72
	1800	2,07	4,06
	2100	1,80	3,53
	2400	1,49	2,94
CaB20	1200	4,01	7,70
	1500	3,13	6,07
	1800	2,13	4,17
	2100	1,70	3,35
	2400	1,57	3,09
CaB40	1200	3,68	7,10
	1500	2,77	5,39
	1800	1,98	3,88
	2100	1,69	3,32
	2400	1,42	2,80
CoB20	1200	3,62	6,99
	1500	3,04	5,90
	1800	2,14	4,19
	2100	1,86	3,65
	2400	1,54	3,04
CoB40	1200	3,44	6,65
	1500	2,85	5,54
	1800	2,00	3,93
	2100	1,73	3,40
	2400	1,45	2,85

The engine was run at 1200, 1500, 1800, 2100, and 2400 rpm engine speeds for all test fuels with H₂ addition. All engine experiments were conducted under no load condition in order to minimize noise and vibration of dynamometer.

A MRU gas analyser was used to measure emissions from the test engine. It is capable to measure CO (0-4000 ppm range and ± 20 ppm accuracy), CO₂ (0-20% range and $\pm 0.5\%$ accuracy), NO (0-1000 ppm and ± 5 ppm accuracy) and NO₂ (0-200 ppm and ± 5 ppm accuracy).

Acoustic and vibration data were recorded via Soundbook™ universal portable measuring system which uses SAMURAI v2.6 software from SINUS Messtechnik GmbH. It is also capable to double integration of the time signal as filtering according to ISO 10816, ISO 7919 and ISO 2954 standards and the measurement range of the vibration meter is 2 Hz to 20 kHz. Sound level meter (SLM) of the software meets the Class 1 SLM according to IEC 60651, IEC 60804, DIN EN 61672-1:2003 standards allowing simultaneous measurements with the frequency weightings A, C, Z.

An accelerometer from PCB electronic (model no: 356A33) with 1.02 mV/(m/s²) sensitivity and ± 4905 m/s² measurement range and a microphone from GRAS (model no: 46AF) half-inch free-field standard microphone set which has 50 mV/Pa sensitivity, 3.15 Hz to 20 kHz frequency range and 17 dB(A) to 149 dB dynamic range were used in order to gathering the acoustic and vibration data. The accelerometer was adhered with quick bonding gels to measure the vibration even in high frequency range and the microphone was set 1 m away from the engine block. The schematic of experimental set-up is shown in fig 1.

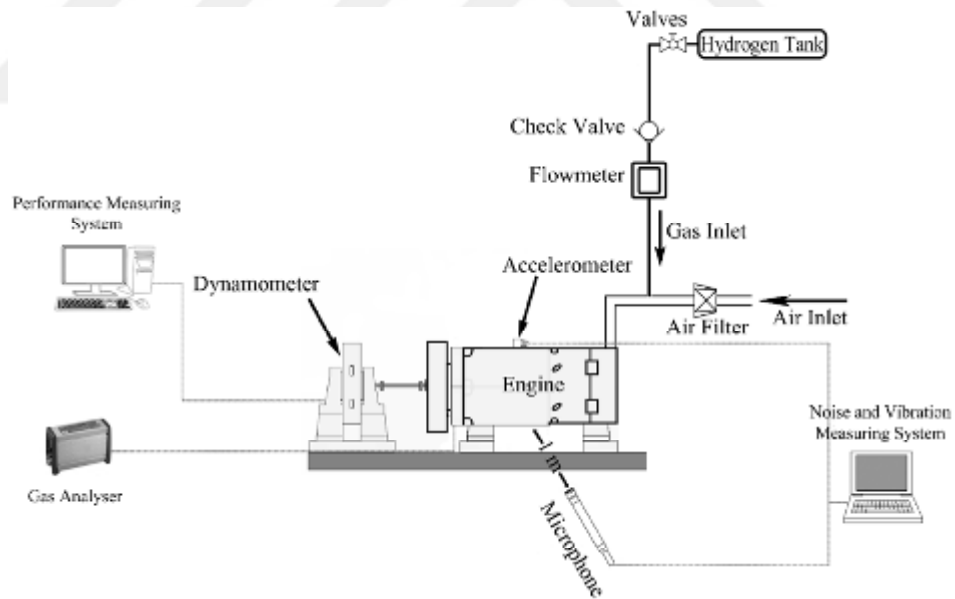


Fig 1. Schematic diagram of the experimental set-up

In vibration comparison of test fuels, the RMS (root mean square) values were considered since it gives an amplitude value by considering time history of the wave. Eq. 2 shows the formula to calculate RMS value.

$$a_w = \sqrt{\frac{1}{T} \int_0^T a_w^2(t) dt} \quad (2)$$

Where;

a_w : weighted acceleration (m/s²)

T : measurement time

Time and frequency domains were analysed in x (longitudinal), y (lateral) and z (vertical) axes, then combined vibration acceleration was calculated by eq. 3.

$$a_{total} = \sqrt{a_{vertical}^2 + a_{lateral}^2 + a_{longitudinal}^2} \quad (3)$$

Result and Discussion

Throughout this study, experimental the engine was fuelled with seven different fuels (D100, SB20, SB40, CaB20, CaB40, CoB20, CoB40), meanwhile two different hydrogen flow rate (H3, H6) was added into the intake air. The engine was run at 1200 rpm, 1500 rpm, 1800 rpm, 2100 rpm, and 2400 rpm engine speeds under no load condition.

Biodiesel fuels were added up to 40% by volume into low sulphur diesel fuel in order to fulfil biodiesel standard of EN 14214. Fuel properties of test fuels and standards of diesel and biodiesel (EN590 and EN14214, respectively) were presented in table 2.

Table 2

Fuel properties of test fuels.

Test Fuels	Density (kg/m ³)	Cetane Number	Kinematic Viscosity at 40°C (mm ² /s)	Lower Heating Value (kJ/kg)	Flash point (°C)
D100	837	59,3	2,7	45857	74,5
EN590	820–845	Min 51	2.0–4.5	-	Min 55
SB20	844	56,5	3,1	44246	101,5
SB40	854	53,6	3,4	43430	106,5
CaB20	846	56,9	3,2	43413	76,7
CaB40	857	54	3,5	42986	83,9
CoB20	847	55,4	3	42266	85,5
CoB40	856	52,1	3,2	41881	91,5
EN 14214	860 – 900	Min 51	3,5 – 5,0	-	Min 120
Hydrogen	0,084	-	-	119930	-

Vibration data of the engine was gathered for 10 seconds long for each experiment from the engine block and the sampling frequency was 51,2 kHz. Previous studies showed that vibration of internal combustion engines were effected by many parameters such as movement of piston-crank mechanism, input from the timing gear system, fittings of the engine, inputs transmitted from the motor body,

flow of cooling factor, inlet and outlet gases, inlet and outlet of fuel through injector, inertia of cam unit's parts, impacts of head's parts [37-38].

Time and frequency spectrum at x (longitudinal)- y (lateral)- z (vertical) axes of experiment engine was shown in figures 2 and 3. The figures illustrated the time and frequency spectrum of D100 without H₂ addition at 1500 rpm and SB40-H6 at 2400 rpm, for sampling at different engine operating condition, fuels and H₂ flow rates. It is clear that the dominant frequency is the twice speed of engine operating speed due to firing frequency of the engine. Upward and downward piston movement caused the maximum RMS value occurred at z- axis and the conversion of linear motion to rotational motion on crankshaft responsible to increase of RMS values at x-axis. Auxiliary equipment primarily results in vibration acceleration at y- axis.

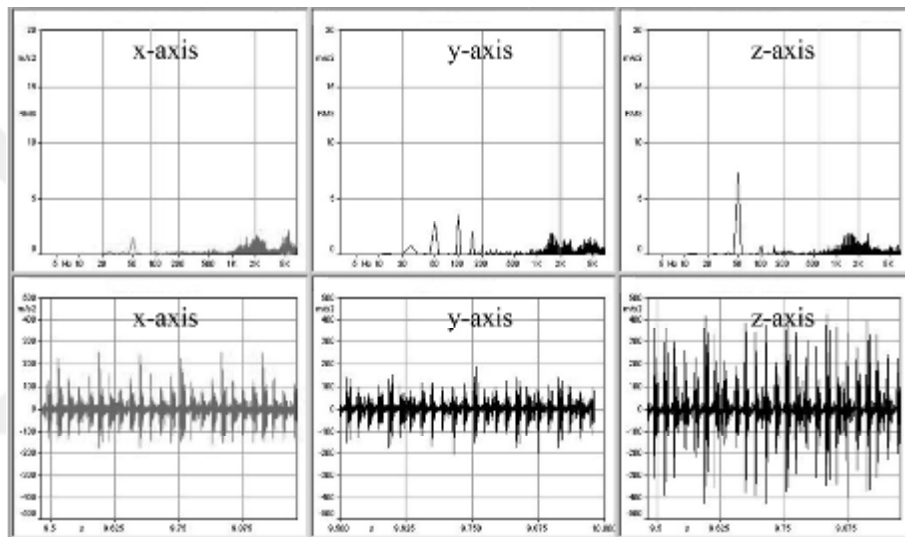


Fig 2. Time and frequency spectrum of the engine (D100 at 1500 rpm)

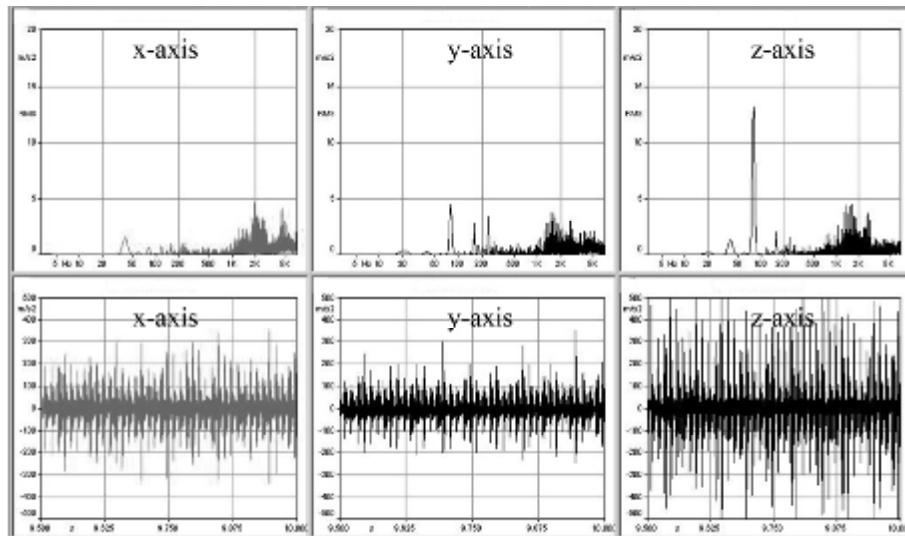


Fig 3. Time and frequency spectrum of the engine (SB40-H6 at 2400 rpm)

The analyses indicated that vibration of the engine was significantly affected by engine speed. a_{total} values of the engine with different fuels and H_2 flow rate were shown in fig 4, 5, 6, 7, and 8. According to these results, vibration acceleration decreased by increasing biodiesel ratio into the blend. The average decrement was found out as 1,72%, 2,38%, 2,37%, 2,79%, 0,5%, and 0,98% for SB20, SB40, CaB20, CaB40, CoB20, and CoB40, respectively compared to D100. This decrement may be due to extra oxygen contamination of biodiesels which result with better combustion quality. H_2 addition was further decreased engine vibration acceleration when it was fuelled with each test fuels. Vibration acceleration was decreased by 1,44% and 3,52% with D100; 2,2% and 3,7% with SB20; 0,86% and 1,94% with SB40; 1,53% and 2,59% with CaB20; 0,32% and 1,36% with CaB40; 1,08% and 2,92% with CoB20; 1,44% and 2,76% with CoB40 by adding H_3 and H_6 gases, respectively into the intake air. Ignition delay and variation in peak pressure rise rate may cause to decrement of engine block vibration with biodiesel and H_2 fuels [32, 39-40].

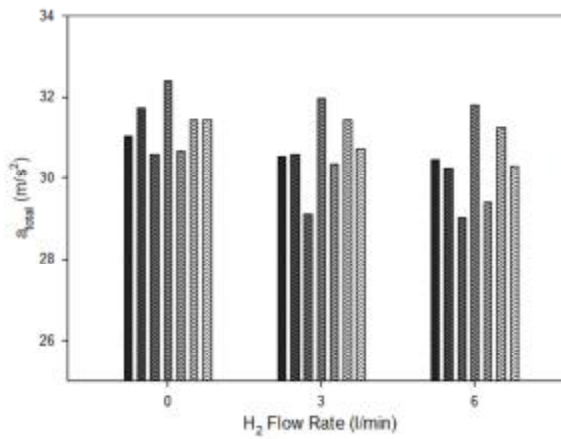


Fig. 4. a_{total} values at 1200 rpm

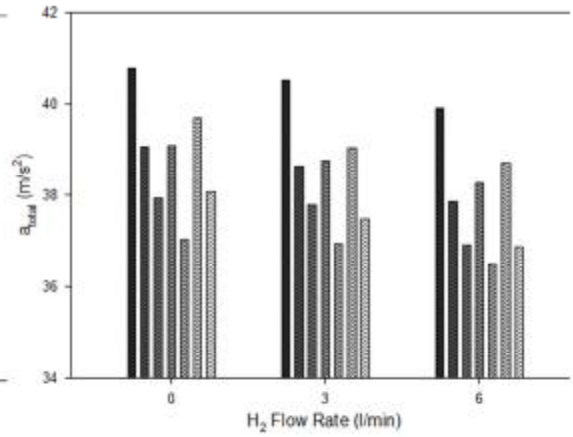


Fig. 5. a_{total} values at 1500 rpm

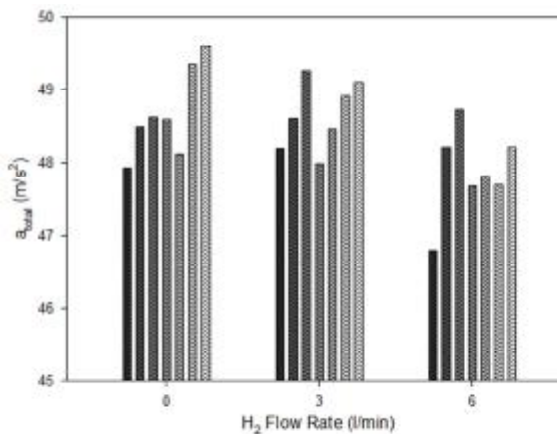


Fig. 6. a_{total} values at 1800 rpm

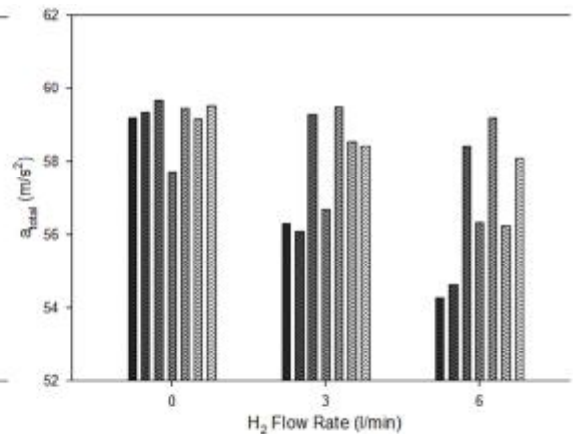


Fig. 7. a_{total} values at 2100 rpm

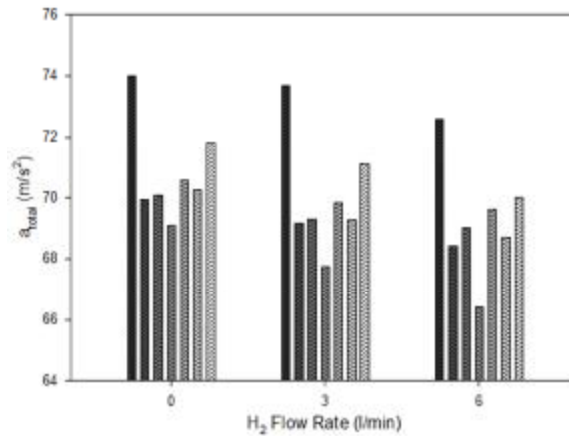


Fig. 8. a_{total} values at 2100 rpm

■ Diesel ■ SB20 ■ SB100 ■ CaB20 ■ CaB100 ■ FB20 ■ FB100

Compression ignition engines are very complex systems from an acoustic point of view due to various dynamic forces exerts on structure with varying stiffness, damping and response characteristics [41].

Throughout this study sound pressure level of the engine was compared according to A- weighted which is similar to perceived by the human ear. To conduct noise tests, the room was specially insulated by sound barriers and also, periphery of dynamometer was further covered by sound absorber panels.

By using biodiesel the sound pressure level of the engine averagely decreased by 0,6 dB(A), 0,5 dB(A), 0,3 dB(A), 0,4 dB(A), 0,2 dB(A), and 0,4 dB(A), for SB20, SB40, CaB20, CaB40, CoB20, and CoB40, respectively compared to D100, whereas higher engine speed significantly increased the noise of the engine.

Addition of H_2 lowered the sound pressure level slightly (0,1 dB(A) for both H3 and H6 additions, that of H0). Although sound pressure level tends to increase with some test fuels with the addition of H_2 , it was generally lowered by addition of H_2 . This situation may also interpret with the differences between combustion characteristic such as ignition delay, peak pressure level, and pressure gradient inside the cylinders when the engine fuelled with various test fuel blends [33,41-42].

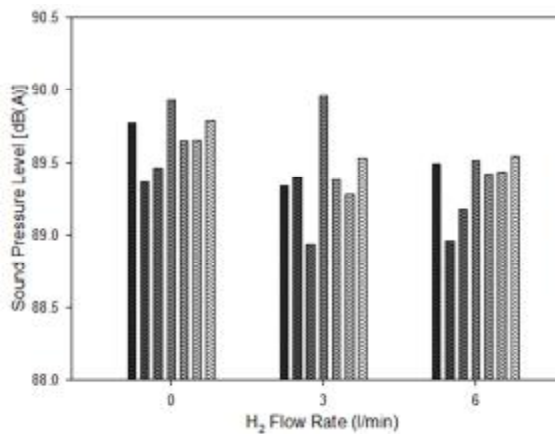


Fig. 9. Sound pressure level at 1200 rpm

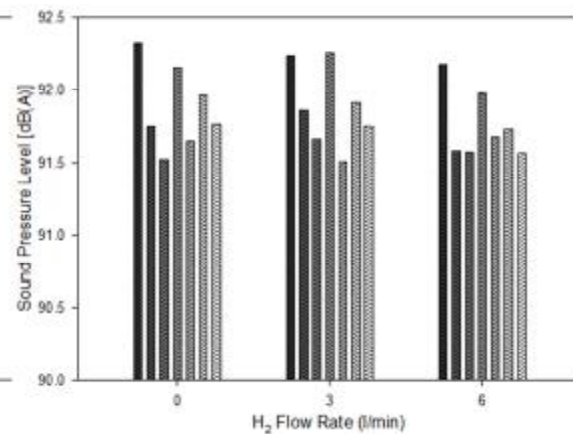


Fig. 10. Sound pressure level at 1500 rpm

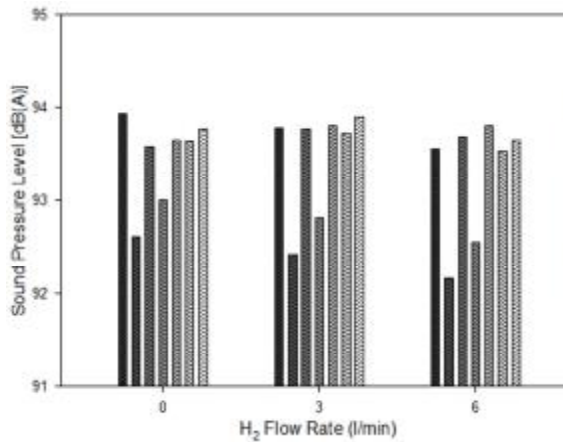


Fig. 11. Sound pressure level at 1800 rpm

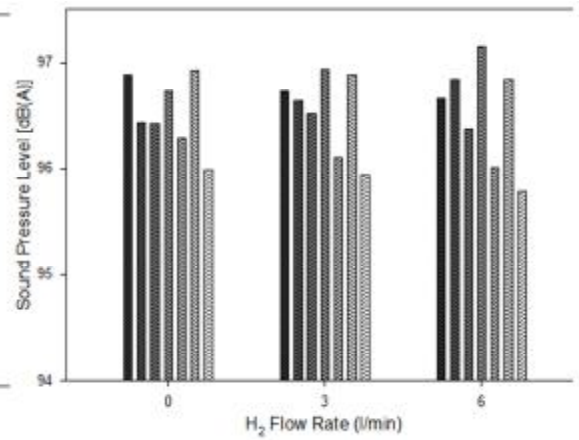


Fig. 12. Sound pressure level at 2100 rpm

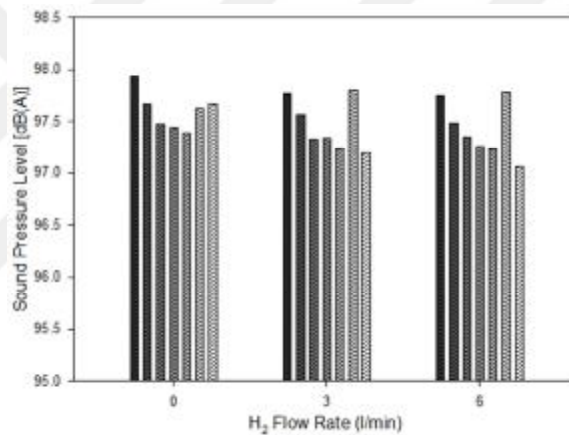


Fig. 13. Sound pressure level at 2400 rpm

Diesel
 SB20
 SB100
 CaB20
 CaB100
 FB20
 FB100

Incomplete combustion is the main reason of CO emission formation [43]. In figure 14, 15, and 16 illustrates the CO values. CO emissions were decreased by using biodiesel blend since the biodiesel contains extra oxygen. Therefore, complete combustion enhanced with biodiesel usage. Furthermore for overall mean values of all test fuels, addition of H₂ further decreased the values by 7,7%, and 11,4%, for addition of H3 and H6, that of without H₂ addition since the gas is absence of carbon atoms [44].

NO_x is the most detrimental pollutant at the combustion stage [45]. NO_x emission values for test fuels with H₂ addition were shown in figure 17, 18, and 19. NO_x formation is affected by higher combustion and flame temperature [46]. There is an increment with biodiesel usage due to extra oxygen content of biodiesel that caused higher combustion temperature. Even though, this trend was also expected with H₂ addition since hydrogen has higher flame speed propagation than diesel and biodiesels, since the experiments in this study has evaluated without any load, decrement in NO_x emissions observed since atmospheric air that fill the cylinders

through intake port replace with H_2 . Thereby, the amount of nitrogen molecules that comes from atmospheric air in cylinders reduced. Also, equivalence ratio at the fuel rich combustion resulted in maintaining a lower cylinder temperature. [47-49]. The average increment was measured as 9,9% and 17,1% with H3 and H6 addition through the intake manifold, respectively, when the engine operated with test fuels.

CO_2 emission is produced by complete combustion of fuel. The concentration of CO_2 has opposite trend to that of concentration of CO owing to improvement of combustion process. Thereby, addition of biodiesel caused to increase of CO_2 emissions. Variation of CO_2 emissions of experiments were shown in figures 20, 21, and 22 for without H_2 addition, H3, and H6 addition, respectively. According to results, compared to none H_2 addition results, H3 addition decreased CO_2 emission by 1,4% and H6 decreased it 2,2%, averagely with the use of test fuels. Due to the absence of carbon in H_2 , and this reduces the overall amount of carbon atoms available for carbon dioxide (or monoxide) formation [48].

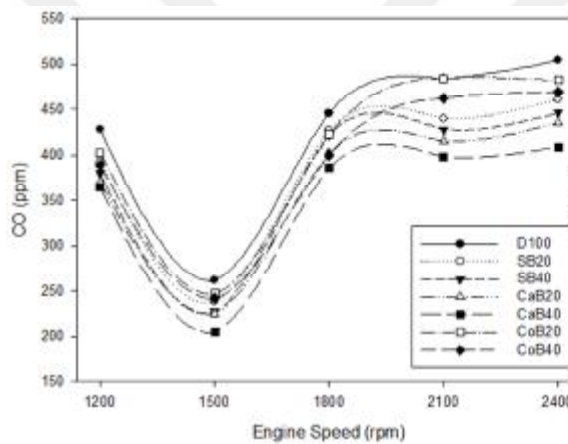


Fig. 14. CO emission values without hydrogen addition

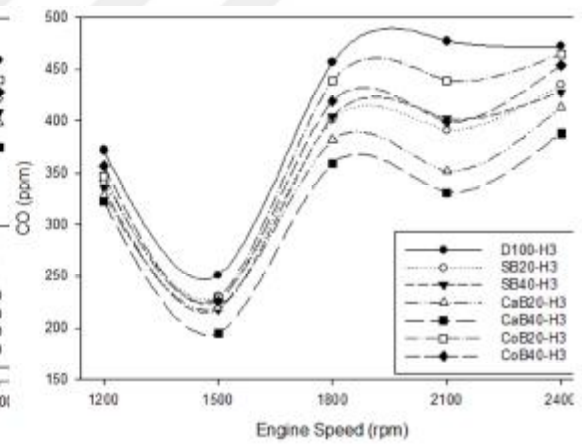


Fig. 15. CO emission values with H3

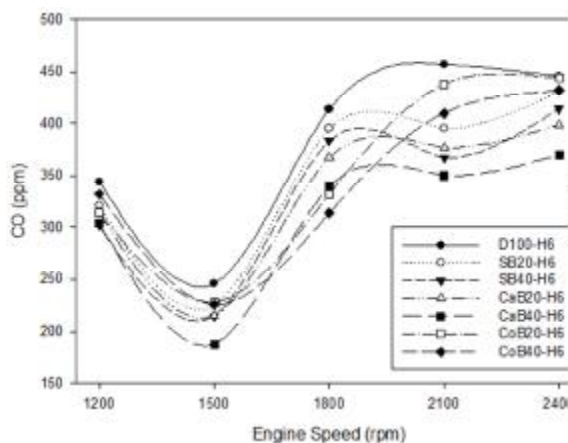


Fig. 16. CO emission values with H6

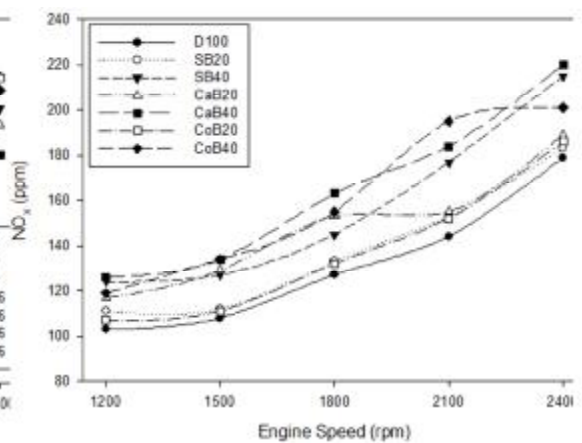


Fig. 17. NO_x emission values without hydrogen addition

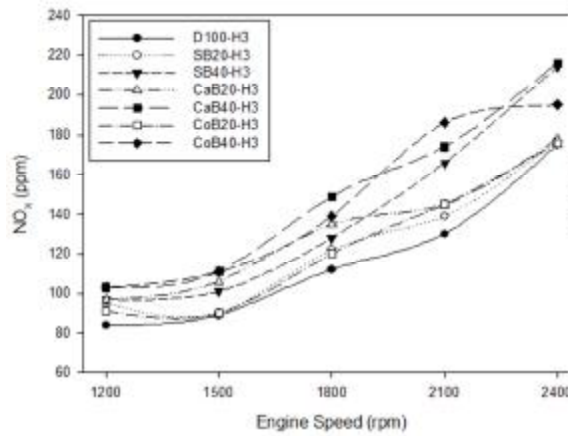


Fig. 18. NO_x emission values with H3

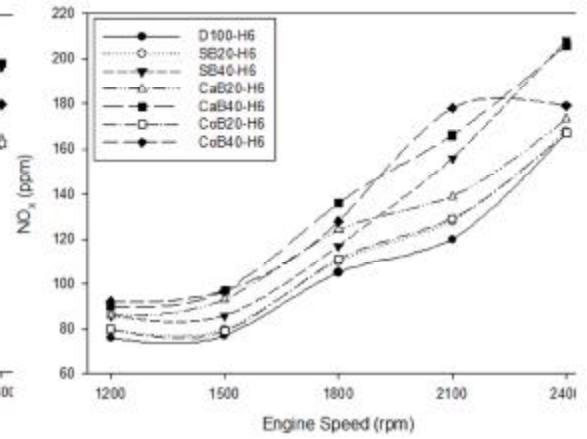


Fig. 19. NO_x emission values with H6

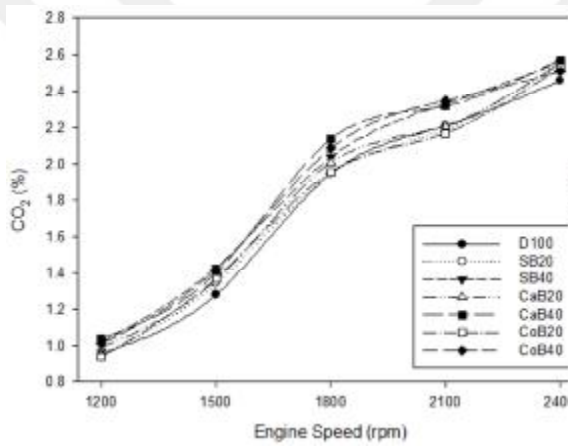


Fig. 20. CO₂ emission values without hydrogen addition

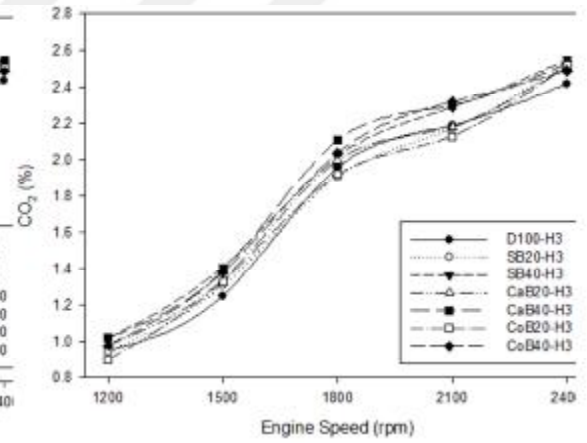


Fig. 21. CO₂ emission values with H3

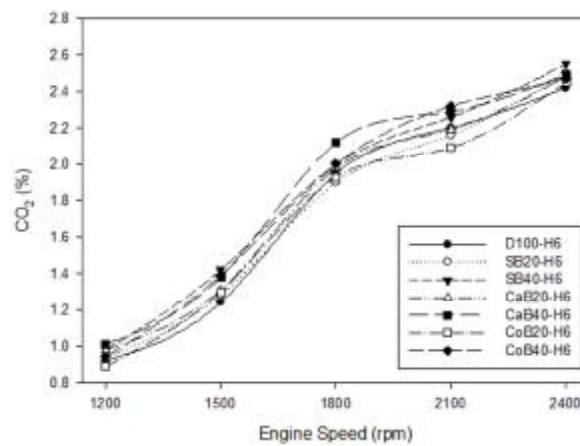


Fig. 22. CO₂ emission values with H6

4. Conclusion

The main objective of this study was to investigate the effect of some alternative fuels on an unmodified compression ignition engine with regard to vibration, noise and exhaust emissions. Throughout the experiments the engine was fuelled with low sulphur diesel, sunflower biodiesel, canola biodiesel, and corn biodiesel blends. Furthermore H_2 was injected into the intake air.

According to experiments and results, following summarizes were brought out:

- Sound pressure level and vibration acceleration of the engine significantly increased with engine speed.
- The dominant frequency was regardless of fuel type and H_2 addition. It significantly affected by engine speed due to upward and downward piston movement.
- Biodiesel blends decreased vibration acceleration and sound pressure level of engine block.
- Averagely, compared to pure diesel fuel, slight sound pressure level [dB(A)] decrement was measured with diesel-biodiesel blend usage.
- Vibration acceleration values further reduced with H_2 gas addition into intake air.
- Sound pressure level generally decreased with H_2 addition.
- Biodiesel usage caused to increment of CO_2 and NO_x emissions whereas, these emissions decreased with H_2 addition. Moreover, CO emission decreased with usage of biodiesel and H_2 .

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References

- [1] Ithnin AM, Noge H, Abdul Kadir H, Jazair W. An overview of utilizing water-in-diesel emulsion fuel in diesel engine and its potential research study. *J Energy Inst* 2014;87:273–88.
- [2] Atmanlı A, İleri E, Yüksel B. Effects of higher ratios of n-butanol addition to diesel–vegetable oil blends on performance and exhaust emissions of a diesel engine. *J Energy Inst* 2015;88:209–20.
- [3] Murcak A, Haşimoğlu C, Çevik İ, Kahraman H. Effect of injection timing to performance of a diesel engine fuelled with different diesel–ethanol mixtures. *Fuel* 2015;153:569–77.
- [4] Shaafi T, Velraj R. Influence of alumina nanoparticles, ethanol and isopropanol blend as additive with diesel–soybean biodiesel blend fuel: Combustion, engine performance and emissions. *Renew Energy* 2015;80:655–63.
- [5] Chen G, Di L, Zhang Q, Zheng Z, Zhang W. Effects of 2,5-dimethylfuran fuel properties coupling with EGR (exhaust gas recirculation) on combustion and emission characteristics in common-rail diesel engines. *Energy* 2015;93:284–93.
- [6] Kaimal VK, Vijayabalan P. A detailed study of combustion characteristics of a DI diesel engine using waste plastic oil and its blends. *Energy Convers Manag* 2015;105:951–6.
- [7] Attia AMA, Kulchitskiy AR. Influence of the structure of water-in-fuel emulsion on diesel engine performance. *Fuel* 2014;116:703–8.
- [8] Lujaji F, Kristóf L, Bereczky A, Mbarawa M. Experimental investigation of fuel properties, engine performance, combustion and emissions of blends containing croton oil, butanol, and diesel on a CI engine. *Fuel* 2011;90:505–10.
- [9] Mwangi JK, Lee W-J, Chang Y-C, Chen C-Y, Wang L-C. An overview: Energy saving and pollution reduction by using green fuel blends in diesel engines. *Appl Energy* 2015;159:214–36.
- [10] Zaker K, Askari MH, Jazayeri A, Ebrahimi R, Zaker B, Ashjaee M. Open

- cycle CFD investigation of SI engine fuelled with hydrogen/methane blends using detailed kinetic mechanism. *Int J Hydrogen Energy* 2015;40:14006–19.
- [11] Karabektas M. The effects of turbocharger on the performance and exhaust emissions of a diesel engine fuelled with biodiesel. *Renew Energy* 2009;34:989–93.
- [12] Muthukumaran N, Saravanan CG, Prasanna Raj Yadav S, Vallinayagam R, Vedharaj S, Roberts WL. Synthesis of cracked Calophyllum inophyllum oil using fly ash catalyst for diesel engine application. *Fuel* 2015;155:68–76.
- [13] Sharma A, Murugan S. Combustion, performance and emission characteristics of a DI diesel engine fuelled with non-petroleum fuel: A study on the role of fuel injection timing. *J Energy Inst* 2014;88:364–75.
- [14] Ali OM, Mamat R, Abdullah NR, Adam A. Analysis of blended fuel properties and engine performance with palm biodiesel e diesel blended fuel. *Renew Energy* 2016;86:59–67.
- [15] Shehata MS, Attia AMA, Razek SMA. Corn and soybean biodiesel blends as alternative fuels for diesel engine at different injection pressures. *Fuel* 2015;161:49–58.
- [16] Harch CA, Rasul MG, Hassan NMS, Bhuiya MMK. Modelling of Engine Performance Fuelled with Second Generation Biodiesel. *Procedia Eng* 2014;90:459–65.
- [17] Ramadhas AS, Jayaraj S, Muraleedharan C. Use of vegetable oils as I.C. engine fuels - A review. *Renew Energy* 2004;29:727–42.
- [18] Can Ö. Combustion characteristics, performance and exhaust emissions of a diesel engine fuelled with a waste cooking oil biodiesel mixture. *Energy Convers Manag* 2014;87:676–86.
- [19] Prakash R, Singh RK, Murugan S. Experimental studies on combustion, performance and emission characteristics of diesel engine using different biodiesel bio oil emulsions. *J Energy Inst* 2015;88:64–75.
- [20] Lešnik L, Vajda B, Žunič Z, Škerget L, Kegl B. The influence of biodiesel fuel on injection characteristics, diesel engine performance, and emission formation. *Appl Energy* 2013;111:558–70.

- [21] Mofijur M, Atabani AE, Masjuki HH, Kalam MA, Masum BM. A study on the effects of promising edible and non-edible biodiesel feedstocks on engine performance and emissions production: A comparative evaluation. *Renew Sustain Energy Rev* 2013;23:391–404.
- [22] Dhar A, Agarwal AK. Performance, emissions and combustion characteristics of Karanja biodiesel in a transportation engine. *Fuel* 2014;119:70–80.
- [23] Al_Dawody MF, Bhatti SK. Experimental and Computational Investigations for Combustion, Performance and Emission Parameters of a Diesel Engine Fuelled with Soybean Biodiesel-Diesel Blends. *Energy Procedia* 2014;52:421–30.
- [24] Karabektas M, Ergen G, Hosoz M. Effects of the blends containing low ratios of alternative fuels on the performance and emission characteristics of a diesel engine. *Fuel* 2013;112:537–41.
- [25] Mat Yasin MH, Yusaf T, Mamat R, Fitri Yusop A. Characterization of a diesel engine operating with a small proportion of methanol as a fuel additive in biodiesel blend. *Appl Energy* 2014;114:865–73.
- [26] Paul G, Datta A, Mandal BK. An Experimental and Numerical Investigation of the Performance, Combustion and Emission Characteristics of a Diesel Engine Fuelled with Jatropha Biodiesel. *Energy Procedia* 2014;54:455–67.
- [27] Shehata MS. Emissions, performance and cylinder pressure of diesel engine fuelled by biodiesel fuel. *Fuel* 2013;112:513–22.
- [28] Hamdan MO, Selim MYE, Al-Omari SAB, Elnajjar E. Hydrogen supplement co-combustion with diesel in compression ignition engine. *Renew Energy* 2015;82:54–60.
- [29] Imran S, Emberson DR, Hussain A, Ali H, Ihracska B, Korakianitis T. Performance and specific emissions contours throughout the operating range of hydrogen-fuelled compression ignition engine with diesel and RME pilot fuels. *Alexandria Eng J* 2015;54:303–14.
- [30] Açıkgöz B, Çelik C, Soyhan HS, Gökalp B, Karabağ B. Emission characteristics of an hydrogen-CH₄ fuelled spark ignition engine. *Fuel* 2015;159:298–307.

- [31] An H, Yang WM, Maghbouli A., Li J, Chou SK, Chua KJ, et al. Numerical investigation on the combustion and emission characteristics of a hydrogen assisted biodiesel combustion in a diesel engine. *Fuel* 2014;120:186–94.
- [32] How HG, Masjuki HH, Kalam M A., Teoh YH. An investigation of the engine performance, emissions and combustion characteristics of coconut biodiesel in a high-pressure common-rail diesel engine. *Energy* 2014;69:749–59.
- [33] Nguyen TA, Mikami M. Effect of hydrogen addition to intake air on combustion noise from a diesel engine. *Int J Hydrogen Energy* 2013;38:4153–62.
- [34] Taghizadeh-Alisaraei A, Ghobadian B, Tavakoli-Hashjin T, Mohtasebi S.S., Vibration analysis of a diesel engine using biodiesel and petrodiesel fuel blends, *Fuel* 2012;102:414–22.
- [35] Gravalos I, Loutridis S, Moshou D, Gialamas T, Kateris D, Tsiropoulos Z, Xyradakis P. Detection of fuel type on a spark ignition engine from engine vibration behaviour. *Applied Thermal Engineering* 2013;54:171-5.
- [36] Redel-Macías MD, Rodríguez-Cantalejo RD, Pinzi S, Cubero-Atienza AJ, Dorado MP. Evaluation of sound quality in a tractor driver cabin based on the effect of biodiesel fatty acid composition. *Fuel* 2014;118:194–201.
- [37] Czech P, Lazarz B, Madej H, Wojnar G, Vibration Diagnosis of Car Motor Engines, *Acta Technica Corviniensis* 2010;3:37–42.
- [38] Tomaszewski F, Szymański G, Frequency Analysis of Vibrations of the Internal Combustion Engine Components in the Diagnosis of Engine Processes, *Arch. Transp.* 2012;24:117–25.
- [39] Zhang Y, Jiang X, Wei L, Zhang J, Tang C, Huang Z. Experimental and modeling study on auto-ignition characteristics of methane/hydrogen blends under engine relevant pressure. *Int J Hydrogen Energy* 2012;37:19168–76.
- [40] Zhang Y, Huang Z, Wei L, Zhang J, Law CK. Experimental and modeling study on ignition delays of lean mixtures of methane, hydrogen, oxygen, and argon at elevated pressures. *Combust Flame* 2012;159:918–31.
- [41] Giakoumis EG, Rakopoulos DC, Rakopoulos CD. Combustion noise radiation during dynamic diesel engine operation including effects of various biofuel

- blends: A review. *Renew Sustain Energy Rev* 2016;54:1099–113.
- [42] Seifi MR, Hassan-Beygi SR, Ghobadian B, Desideri U, Antonelli M. Experimental investigation of a diesel engine power, torque and noise emission using water-diesel emulsions. *Fuel* 2016;166:392–9.
 - [43] Li L, Wang J, Wang Z, Xiao J. Combustion and emission characteristics of diesel engine fuelled with diesel/biodiesel/pentanol fuel blends. *Fuel* 2015;156:211–8.
 - [44] Yilmaz AC, Uludamar E, Aydin K. Effect of hydroxy (HHO) gas addition on performance and exhaust emissions in compression ignition engines. *Int J Hydrogen Energy* 2010;35:11366–72.
 - [45] Velmurugan K, Sathiyagnanam. Impact of antioxidants on NO_x emissions from a mango seed biodiesel powered DI diesel engine. *Alexandria Eng J* 2016; 55:715–22.
 - [46] Tüccar G, Özgür T, Aydın K. Effect of diesel–microalgae biodiesel–butanol blends on performance and emissions of diesel engine. *Fuel* 2014;132:47–52.
 - [47] Deb M, Sastry GRK, Bose PK, Banerjee R. An experimental study on combustion, performance and emission analysis of a single cylinder, 4-stroke DI-diesel engine using hydrogen in dual fuel mode of operation. *Int J Hydrogen Energy* 2015;40:8586–98.
 - [48] Jhang SR, Chen KS, Lin SL, Lin YC, Cheng, WL. Reducing pollutant emissions from a heavy-duty diesel engine by using hydrogen additions. *Fuel* 2016;172:89–95.
 - [49] Karagöz Y, Sandalcı T, Yüksek L, Dalkılıç AS. Engine performance and emission effects of diesel burns enriched by hydrogen on different engine loads. *Int J Hydrogen Energy* 2015;40:6702–13

VIBRATION ANALYSIS OF A DIESEL ENGINE FUELLED WITH SUNFLOWER AND CANOLA BIODIESELS

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Abstract

Biodiesel is one of the most popular alternative fuel. The usage of biodiesel is increasing day by day. Therefore, all effects of biodiesel on internal combustion engines must be known. In this study, vibration effect of canola (rapeseed), sunflower biodiesel and their blends with low sulphur diesel fuel was investigated. Fuels were tested in a four cylinder four stroke diesel engine at 1300, 1600, 1900, 2200, 2500 and 2800 rpm engine speed. The results showed that with the use of biodiesel blend with low sulphur diesel fuel up to 40% proportions, vibration values get significantly lower at all engine speed. The least vibration value for most of the fuel was observed with the use of 60% biodiesel blend. The results were also individually interpreted in longitude, vertical and lateral axes.

Keywords: Vibration, Canola Biodiesel, Sunflower Biodiesel, Internal Combustion Engine

1. INTRODUCTION

Alternative fuels become more important day by day due to depletion of petroleum based fuels. Many countries are mandate by legislations and support the interest in biofuels such as European union (EU) countries which are aim to get %10 of the transport fuel of every EU country from renewable sources [1]. Because of its many

advantages, biodiesel is the most prominence alternative fuel. Biodiesel becomes important for compression ignition engines due to reduction of unburned hydrocarbons, particulars, carbon monoxide, and sulphur oxide exhaust emissions and ease of production [2-3]. Moreover it is renewable, non-toxic and biodegradable fuel [4]. Biodiesel can be derived from plants oil or animal fats via a transesterification reaction with alcohols such as methanol and ethanol [5-6]. Recently, the usage amount of biodiesel dramatically increases mainly due to its unlimited source and modification on diesel engines are unnecessary for the usage of biodiesel as a fuel [7].

The effect of biodiesel fuel must be well known for further engine development and engine maintenance. There is limited study about vibration effect of biodiesel fuels on diesel engines.

In vehicles, engines can generate disturbing forces at different frequencies and causes passenger discomfort [8]. Vibration of internal combustion engine is influenced by burning pressure, the movement of piston-crank mechanism, input from the timing gear system, inputs resulting from the work of the fittings of the engine, inputs transmitted from the motor body, flow of cooling factor, inlet and outlet gases, inlet and outlet of fuel through injector, inertia of cam unit's parts, impacts of head's parts [9-10].

Some researchers examined the vibration characteristic of internal combustion engines which were fuelled with alternative fuels. How et al. (2014) investigated combustion, vibration characteristics, performance and emissions of a high pressured common rail diesel engine which is fuelled with coconut biodiesel blends [11]. Gravalos et al. (2013) presented a paper about vibration behaviour of a spark engine fuelled with unleaded gasoline, ethanol, and methanol blends [12]. Taghizadeh-Alisaraei et al. (2012) studied vibration effect of a biodiesel and its blends on four-stroke six cylinders diesel engine at different rpms [13]. Since canola and sunflower oil is the principal feedstock of Europe, in this paper vibration effect of canola and sunflower biodiesels at different engine speeds were investigated in longitudinal, vertical and lateral axes. In literature, researchers gathered vibration data from engine block, which is far from the chassis connection of a vehicle. Therefore, in this study,

accelerometer was adhered on engine support to observe engine vibration just before transmitted to chassis.

2. MATERIAL AND METHOD

2.1. Test Fuels

In this study, commercial low sulphur diesel (D), sunflower biodiesel (S100), canola biodiesel (C100) and their blends 20%, 40%, 60% and 80% by volume with diesel fuel (S20, C20, S40, C40, S60, C60 and S80, C80 respectively) were used to conduct the engine experiments.

Commercial sunflower and canola oil were supplied from a local market and used without any further purification. Biodiesels were produced via the transesterification method. In this reaction, methanol and sodium hydroxide were used as reactant and catalyst. The mixture was heated up to 60°C and kept at this temperature for 90 minutes by stirring. After the reaction period, the crude methyl ester was waited at separating funnel for 8 hours. And then, crude glycerine was separated from methyl ester. Finally, the crude methyl ester was washed by warm water until the washed water became clear and then it dried at 110 °C for 1 hour. Finally washed and dried methyl ester was passed through a filter.

Fuel properties were analysed by; Zeltex ZX 440 NIR petroleum analyzer with an accuracy of ± 0.5 for determining cetane number; Tanaka AKV 202 auto kinematic viscosity test for determining the viscosity; Kyoto electronics DA-130 for density measurement and IKA-Werke C2000 Bomb Calorimeter for gross heating value determination.

2.2. Experimental Engine

Experiments were performed on a Mitsubishi Canter 4D31, four stroke, four cylinder diesel engine and TT electric AMP 160-4B electrical dynamometer. Experimental layout was shown in Figure 1 and engine specifications were given in Table 1.

Before the experimental measurements were gathered, the engine had been warmed up to constant operating temperature. Then, fuels were tested at 1300, 1600, 1900, 2200, 2500 and 2800 rpm engine speeds.

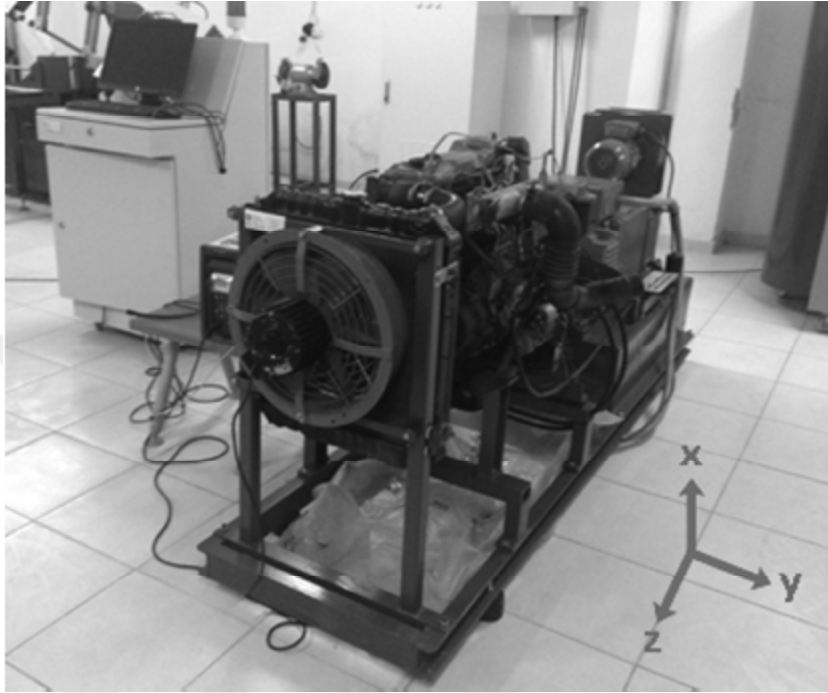


Figure 1. Layout of experimental setup

Table 1. Technical specifications of the test engine

Brand	Mitsubishi Canter
Model	4D31
Configuration	In line 4
Type	Direct injection diesel with glow plug
Displacement	3298cc
Bore	100
Stroke	105
Power	91 HP @ 3500rpm
Torque	223 Nm @ 2200rpm
Oil Cooler	Water cooled

2.3. Vibration Meter and Accelerometer

Vibration data was recorded with the HARMONIETM measuring system, Samurai v2.6 from SINUS Messtechnik GmbH and the ToughbookTM CF-18 portable PC. It is capable to double integration of the time signal as filtering according to ISO 10816, ISO 7919 and ISO 2954 standards and the measurement range of the vibration meter is 2 Hz to 20 kHz.

Triaxial ICP® accelerometer sensor from PCB electronics model 356A33 was adhered on engine support with quick bonding gels to measure the vibration even in high frequency range. Vibration data were gathered in three orthogonal axes of the engine (x- vertical axis; y- lateral axis, and z- longitudinal axis).

2.4. Calculations

The results mostly described as RMS value. The RMS value is the most relevant measure of vibration level since it gives an amplitude value by considering time history of the wave. Formulas, which were used to calculate RMS value, were presented in the following equations. In Equation 1. a_w (m/s²) represents the weighted acceleration and T represents measurement time

$$a_w = \sqrt{\frac{1}{T} \int_0^T a_w^2(t) dt}$$

(1)

Total vibration acceleration (total a_{RMS}) is the value to show combined acceleration of three axes. It was calculated by the formula given in Equation 2.

$$Total\ a_{RMS} = \sqrt{a_{vertical}^2 + a_{lateral}^2 + a_{longitudinal}^2}$$

(2)

3. RESULT AND DISCUSSION

Sunflower and canola methyl esters were used as biodiesel fuels and 100% low sulphur diesel fuel was used as reference fuel. Mixtures of the test fuels were prepared just before the experiments. Quality measurements of the fuels were

performed according to TS EN 14214 biodiesel standard and EN 590 diesel standard. Fuel properties were given in Table 2.

Table 2. Fuel properties of the test fuels.

Test Fuels	Density (kg/l)	Cetane Number	Kinematic Viscosity at 40°C (mm²/s)	Gross Heating Value (kJ/kg)
Low Sulphur Diesel	0,837	59,3	2,7	45857
S20	0,844	53,8	4,2	44246
S40	0,854	53,0	4,5	43430
S60	0,865	50,9	4,6	42472
S80	0,876	47,6	5,1	41388
S100	0,886	44,5	5,5	39149
C20	0,846	54,3	4,5	43413
C40	0,857	53,4	4,8	42986
C60	0,867	51,7	5	41756
C80	0,877	49	5,2	40129
C100	0,883	46	5,4	38363

RMS values of test engine at three orthogonal axes were illustrated in Figure 2. Previous studies were indicated that upward and downward movement of engine pistons primarily responsible of vertical motion whereas, longitudinal motion affected by torque variation and other auxiliary equipment cause the engine vibrate at lateral axis [12].

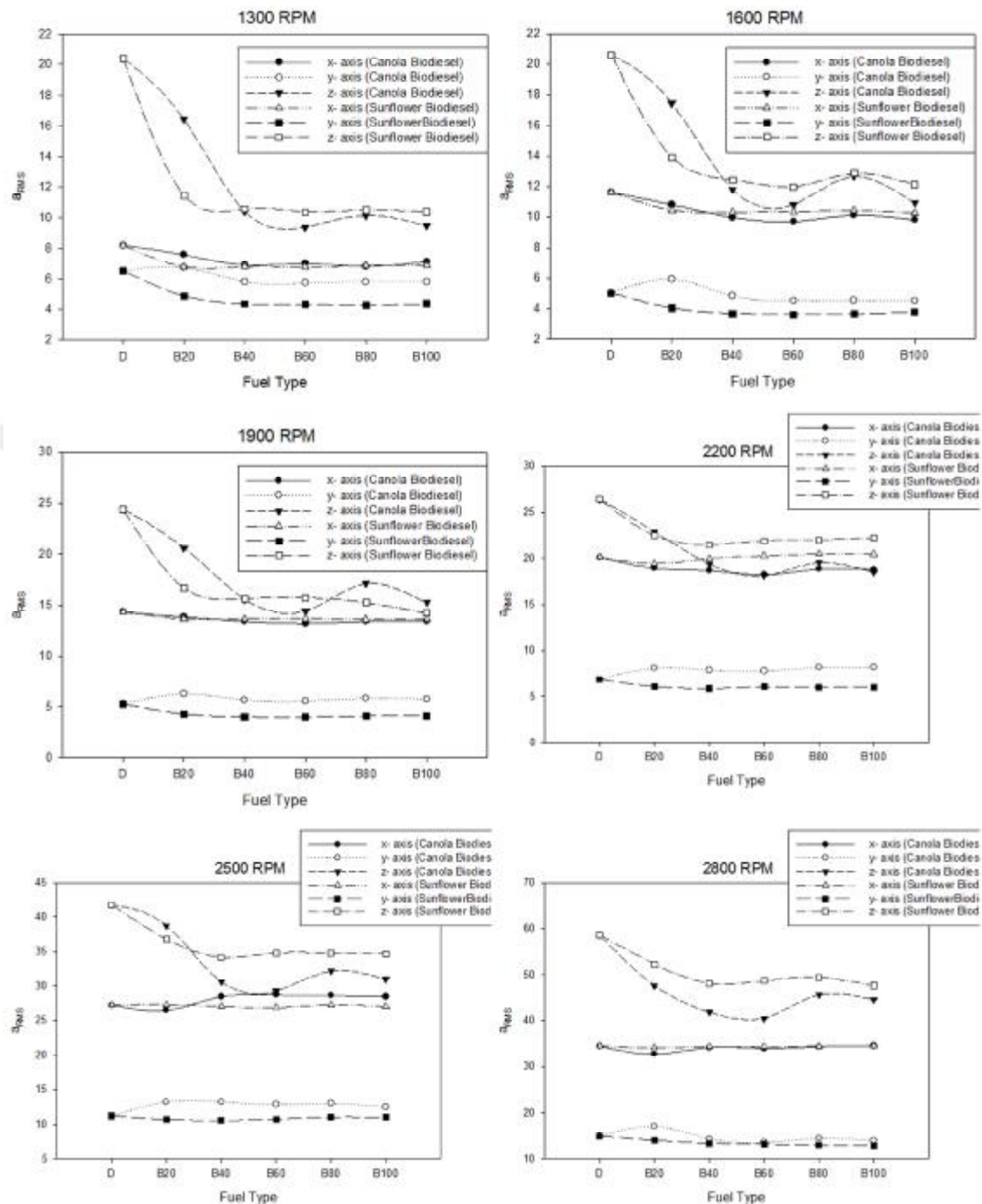


Figure 2. RMS values of the test engine at three orthogonal axes with various engine operating speed

Total a_{rms} values of the engine which fuelled with sunflower and canola biodiesels were presented in Figures 3 and 4, respectively. The results indicated as total a_{rms} value according to different engine speeds. Engine speed was significantly affected

the engine vibration severity at every fuel. Up to 60% canola and sunflower biodiesel addition, total a_{rms} values were decreased and the least vibration acceleration observed with this blend ratio. For the blend of 80%, the total a_{rms} values started to increase. However, pure biodiesel caused slight reduction compared to 80% blends. This trend was observed at all engine speeds for most of the test fuel. In addition, it should be pointed out that the descents of total a_{rms} values were more significant until 40% biodiesel proportion. Addition of canola biodiesel decreased vibration severity more than sunflower biodiesel addition.

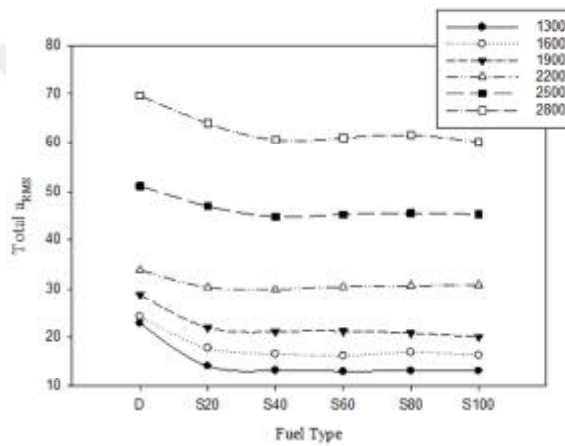


Figure 3. Total a_{RMS} values of sunflower biodiesel

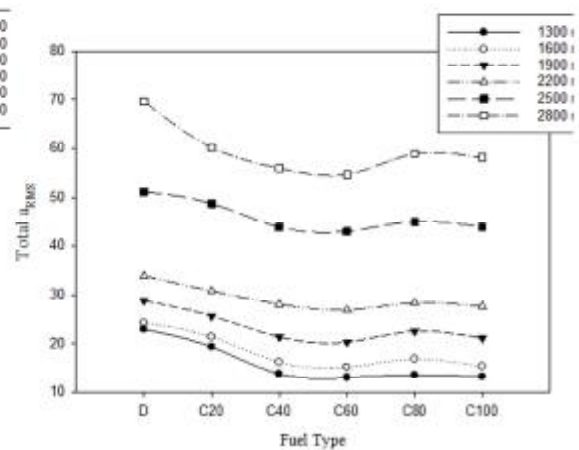


Figure 4. Total a_{RMS} values of canola biodiesel

Theoretically, at 1300 rpm, 1600 rpm, 1900 rpm, 2200 rpm, 2500 rpm, and 2800 rpm engine speeds, ignition frequency of four cylinder four stroke diesel engine are 43,33 Hz, 53,33 Hz, 63,33 Hz, 73,33 Hz, 83,33 Hz, and 93,33 Hz, respectively. In Figure 5, spectrums of the engine vibration was presented at 2200 rpm engine speed when it was fuelled with low sulphur diesel fuel. It can be seen from the figure that the dominant frequency was the piston stroke frequency (73,33 Hz) of the engine occurred at x- (vertical) axis due to the upward and downward movement of the pistons. Fluid impact or mechanical impact such as eroding of ball bearing may have caused vibration at high frequencies [14]. These reasons may have led to the highest vibration acceleration occurred in z- (longitudinal) axis. According to fuel type, at different engine speeds, vibration acceleration significantly changed along x- and z- axes whereas slight differences were observed at y- (lateral) axis. Due to vibration at

x- axis depends on downward-upward piston movement, vibration at this axis increased with engine speed and the conversion of linear motion to rotational motion, a component of vertical force was directly transferred to the z- axes [12].

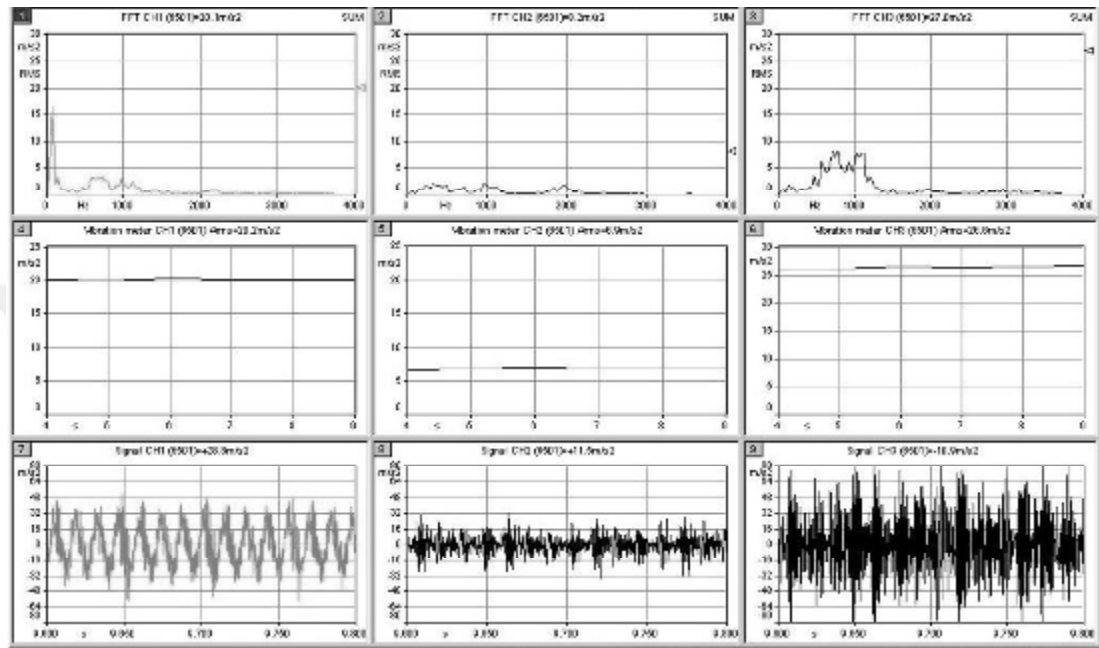


Figure 5. Spectrums of the engine vibration in three axes at 2200 rpm engine speed signal recorded fuelled with low sulphur diesel fuel

4. CONCLUSION

This study was carried out for investigation of diesel engine vibration characteristic which was fuelled with canola and sunflower biodiesels. Contrary to the literature, accelerometer was adhered on engine support, where it connected to the chassis. The test engine was run at six engine speeds with low sulphur diesel, biodiesel fuels and their proportions.

Following conclusions have been summarized;

- Ø Vibration amplitude increased with engine speed.
- Ø Canola and sunflower biodiesel addition into the low sulphur diesel fuel decreased the vibration acceleration of the diesel engine. Addition of canola biodiesel decreased vibration severity more than sunflower biodiesel addition.

- Ø Up to 40% biodiesel blend of canola and sunflower biodiesels with low sulphur diesel fuel, vibration values significantly improved, and the least value observed with 60% biodiesel blend for most of the test fuel.
- Ø The results also showed that, even though total a_{rms} of all frequencies were highest at longitude axis, at all engine speeds; the maximum vibration amplitude occurred in vertical axis due to upward and downward piston movement.

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References

1. Roy MM, Wang W, Bujold J (2013) Biodiesel production and comparison of emissions of a DI diesel engine fuelled by biodiesel–diesel and canola oil–diesel blends at high idling operations. *Applied Energy* 106: 198-208.
2. Bergthorson JM, Thomson MJ (2015) A review of the combustion and emissions properties of advanced transportation biofuels and their impact on existing and future engines. *Renewable and Sustainable Energy Reviews* 42: 1393-1417.
3. Talebian-Kiakalaieh A, Amin NA S, Mazaheri H (2013) A review on novel processes of biodiesel production from waste cooking oil. *Applied Energy*, 104: 683-710.
4. Arbab MI, Masjuki HH, Varman M, Kalam MA, Imtenan S, Sajjad H (2013) Fuel Properties, Engine Performance and Emission Characteristic of Common Biodiesels as a Renewable and Sustainable Source of Fuel. *Renewable and Sustainable Energy Reviews* 22: 133-147.
5. Lee KT, Lim S, Pang YL, Ong HC, Chong WT (2014) Integration of reactive extraction with supercritical fluids for process intensification of biodiesel production: Prospects and recent advances. *Progress in Energy and Combustion Science* 45: 54-78.
6. Farobie O, Yanagida T, Matsumura Y (2014) New approach of catalyst-free biodiesel production from canola oil in supercritical tert-butyl methyl ether (MTBE). *Fuel* 135:172-181.
7. Özener O, Yüksel L, Ergenç AT, Özkan M (2014) Effects of soybean biodiesel on a DI diesel engine performance, emission and combustion characteristics. *Fuel* 115: 875-883.
8. Yu Y, Naganathan NG, Dukkupati RV (2001) A literature review of automotive vehicle engine mounting systems. *Mechanism and Machine Theory* 36: 123-142.
9. Czech P, Lazarz B, Madej H, Wojnar G (2010) Vibration Diagnosis of Car Motor Engines. *Acta Technica Corviniensis– Bulletin of Engineering* 3: 37-42.

10. Tomaszewski F, Szymanski GM (2012) Frequency analysis of vibrations of the internal combustion engine components in the diagnosis of engine processes. *The Archives of Transport* 14: 117-125.
11. How HG, Masjuki HH, Kalam MA, Teoh YH (2014) An investigation of the engine performance, emissions and combustion characteristics of coconut biodiesel in a high-pressure common-rail diesel engine. *Energy* 69: 749-759.
12. Gravalos I, Loutridis S, Moshou D, Gialamas T, Kateris D, et al. (2013) Detection of fuel type on a spark ignition engine from engine vibration behaviour. *Applied Thermal Engineering* 54: 171-175.
13. Taghizadeh-Alisaraei A, Ghobadian B, Tavakoli-Hashjin T (2012) Vibration analysis of a diesel engine using biodiesel and petrodiesel fuel blends. *Fuel* 102: 414-422.
14. Chen J, Randall RB, Peeters B (2016) Advanced diagnostic system for piston slap faults in IC engines, based on the non-stationary characteristics of the vibration signals. *Mechanical Systems and Signal Processing*, In press: 1–21.