ANALYSIS OF LONG-CHAIN ALCOHOL-BIODIESEL-DIESEL TRI-FUEL BLENDS ON COMBUSTION CHARACTERISTICS, ENGINE PERFORMANCES AND EXHAUST EMISSIONS OF DIESEL ENGINE

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ZUHAIRA BINTI ABDULLAH

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ABSTRAK

Enjin diesel merupakan sumber utama tenaga pendorong yang digunakan untuk pengangkutan kereta, industri berat dan jentera pertanian. Ia terkenal dengan tenaga yang cekap dan prestasi tinggi dalam pembakaran. Di samping itu, ia juga diketahui dengan kelebihan dari segi daya kilas yang tinggi, kecekapan tinggi, serta kebolehpercayaan dengan kos operasi yang rendah. Walau bagaimanapun, berdasarkan krisis tenaga pengeluaran bahan api diesel (DF) dari bahan api fosil, telah diramalkan bahawa takungan bahan bakar fosil dunia akan habis pada tahun 2070. Selain itu, bahan bakar fosil adalah sumber utama yang tidak boleh diperbaharui, tidak boleh diguna semula, yang mana bekalan sekarang sangat terhad. Di samping itu, kekurangan prestasi enjin pada rantaian pendek alcohol dan perbezaan nisbah isipadu bahan bakar. Dalam usaha untuk menangani isu-isu ini, pelbagai gabungan campuran alkohol rantaian panjang-biodiesel-diesel bahan bakar dianalisa berdasarkan ciri-ciri pembakaran, prestasi enjin dan pelepasan ekzos pada enjin diesel. Kajian ini mempunyai tiga objektif; (i) untuk menentukan kestabilan dan sifat fizikal D80-B10-PE5, D80-B10-PE10, D75-B10-PE15, D85-B10-HE5, D80-B10-HE10 dan D75-B10-HE15, (ii) untuk mengkaji ciri-ciri pembakaran, prestasi enjin, serta pelepasan ekzos campuran bahan bakar, dan (iii) untuk menentukan nisbah gabungan optimum D80-B10-PE5, D80-B10-PE10, D75-B10-PE15, D85-B10-HE5, D80-B10-HE10 dan D75-B10-HE15 berdasarkan prestasi enjin dengan menggunakan perisian kaedah tindak balas permukaan (RSM). Ujian ini dijalankan pada YANMAR TF120M merupakan silinder tunggal, dan enjin diesel suntikan langsung. Eksperimen dilakukan pada lima beban enjin 0%, 25%, 50%, 75% dan 100% pada kelajuan enjin tetap 1800 rpm. Bahan bakar ujian mengandungi nisbah 5%, 10% dan 15% masing-masing pentanol dan heksanol, ditambah dengan ketetapan 10% nisbah isipadu metil ester minyak kelapa sawit (POME), juga dicampur dengan 85%, 80% dan 75% DF, oleh itu menamakannya dengan, D80-B10-PE5, D80-B10-PE10, D75-B10-PE15, D85-B10-HE5, D80-B10-HE10 dan D75-B10-HE15. Hasil keseluruhan kemudiannya dibandingkan dengan DF dan B100 sebagai garis dasar. Hasil pemerhatian kestabilan menunjukkan bahawa D85-B10-PE5, D80-B10-PE10, D75-B10-PE15, D85-B10-HE5, D80-B10-HE10 dan D75-B10-HE15 tidak menunjukkan pemisahan fasa. Sifat thermo-fizikal dibandingkan dengan B100, nilai kalori meningkat sebanyak 11.45% dan 11.38% untuk D80-B10-PE10 dan D75-B10-HE15. Juga, kelikatan kinematik D80-B10-PE10 dan D75-B10-HE15 menunjukkan pengurangan sebanyak 27.96% dan 23.23%, disebabkan tambahan alcohol rantaian panjang. Di samping itu, tekanan dalam silinder pada beban enjin 100%, tekanan puncak maksimum di D75-B10-PE15 dan D85-B10-HE5 menurun sebanyak 0.66% dan 0.54% berbanding DF. Ini disebabkan oleh suhu tekanan dalam silinder yang lebih tinggi yang melemahkan kesan penyejukan pada penambahan alkohol rantaian panjang. Kadar pelepasan haba maksimum menunjukkan D75-B10-HE15 meningkat sebanyak 31.98% berbanding DF pada beban enjin 100%. Tambahan pula, prestasi enjin dari segi kecekapan terma brek meningkat sebanyak 10.37%, manakala penggunaan bahan bakar khusus brek menurun kepada 13.75% untuk D80-B10-PE10 berbanding DF pada beban enjin 100%. Selain itu, pengurangan pelepasan ekzos yang menghasilkan CO_2, dan NO_x menurun sebanyak 6.79% dan 20.65% untuk D75-B10-PE15 pada beban enjin 100% berbanding DF. Ini disebabkan oleh nombor cetane dan kadar kelikatan yang rendah pada kepekatan alkohol rantaian panjang yang paling tinggi. Akhir sekali, pemilihan terbaik nisbah campuran optimum adalah dekat dengan D80-B10-PE10 dan D75-B10-HE15.

ABSTRACT

Diesel engine is the main source of energy propulsion that is used for automobile transportations, heavy industries and agriculture machinery. It is well known for its friction efficient and high performance in combustion. Additionally, it is also known for its advantages in terms of high torque, high efficiency, as well as reliability with low operating cost. However, based on the energy crisis of production diesel fuel (DF) from fossil fuels, it has been predicted that the world's fossil fuel reservoir would be depleted in 2070. Other than that, fossil fuel is the primary source that is non-renewable and non-reusable, which current stock is very limited. In addition, the disadvantages of engine performance when DF was blended to short-chain alcohol and different volume ratio of fuel blends. In order to address these issues, in this study, a various blend of long-chain alcohol-biodiesel-diesel tri-fuel blends were analysed based on combustion characteristics, engine performances and exhaust emissions. The current study has three objectives; (i) to determine the stability and thermo-physical of D85-B10-PE5, D80-B10-PE10, D75-B10-PE15, D85-B10-HE5, D80-B10-HE10 and D75-B10-HE15, (ii) to investigate the combustion characteristics, engine performances and exhaust emissions of long-chain alcohol-biodiesel-diesel tri-fuel blends, and (iii) to determine the optimum blends ratio of D85-B10-PE5, D80-B10-PE10, D75-B10-PE15, D85-B10-HE5, D80-B10-HE10 and D75-B10-HE15 based on engine performance by using Response Surface Methodology (RSM) software. The test was conducted on YANMAR TF120M engine single cylinder, and direct injection diesel engine. The experiments were conducted on five engine loads of 0%, 25%, 50%, 75% and 100% at constant engine speed of 1800 rpm. The test fuel consists of 5%, 10% and 15% volume ratio of pentanol and hexanol, added with remaining 10% constant volume ratio of palm oil methyl ester (POME), and blended with 85%, 80% and 75% of DF, named fuel as D85-B10-PE5, D80-B10-PE10, D75-B10-PE15, D85-B10-HE5, D80-B10-HE10 and D75-B10-HE15. The overall results are then compared with DF and B100 as the baseline. The result of stability observation reveals that D85-B10-PE5, D80-B10-PE10, D75-B10-PE15, D85-B10-HE5, D80-B10-HE10 and D75-B10-HE15 did not show any phase separation. The thermo-physical properties compared to the B100, calorific value increased by 11.45% and 11.38% for the D80-B10-PE10 and D75-B10-HE15 respectively. Also, the kinematic viscosity of D80-B10-PE10 and D75-B10-HE15 showed a reduction of 27.96% and 23.23% respectively, due to the addition of long-chain alcohols. In addition, in-cylinder pressure at 100% engine load, showed maximum peak pressure in D75-B10-PE15 and D85-B10-HE5 decreases by 0.66% and 0.54% compared to DF. This is due to higher in-cylinder pressure temperature that weakened the cooling effect of addition long-chain alcohol. The maximum heat release rate showed D75-B10-HE15 increased by 31.98% compared to DF at 100% engine load. Furthermore, the engine performance in terms of brake thermal efficiency increased by 10.37%, while brake specific fuel consumption decreased by 13.75% for D80-B10-PE10 compared to DF at 100% engine load. Besides, the reduction in exhaust emissions that produced CO_2, and NO_x decreased by 6.79% and 20.65% for D75-B10-PE15 at 100% engine load compared to DF. This is due to the lower cetane number and viscosity that is at highest volume concentration of long-chain alcohol. Lastly, the best selection of optimum blend ratio is close to D80-B10-PE10 and D75-B10-HE15.

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LIST OF SYMBOLS

A	Area
C	Compression stroke
κ	Ratio of specific heat
L	Length
$\dot{m}$	Mass flow rate
N	Rotational speed
P	Cylinder pressure
P_e	Engine power
Q	Heat transfer
r	Radius
T	Torque
V	Cylinder volume
W	Net load
X	Uncertainty of variables
Y	Uncertainty of parameter
λ	Relative air-fuel ratio
θ	Crank angle
%	Percentage
℃	Degree celsius

LIST OF ABBREVIATIONS

PE	1-pentanol
HE	2-ethyl 1-hexanol
ASTM	American Society for Testing and Material
BHA	2,6-di-tert-butyl-4-methylphenol
BHT	2(3)-tert-butyl-4-methoxyphenol
BP	British Petroleum
BSEC	Brake Specific Energy Consumption
BSFC	Brake Specific Fuel Consumption
B.t.u	British Thermal Unit
bTDC	Before Top Dead Centre
BTE	Brake Thermal Efficiency
CAD	Crank Angle Degree
CI	Compression Ignition
CNT	Carbon nanotubes
CO	Carbon monoxide
CO_2	Carbon dioxide
DAQ	Data Acquisitions
DF	Diesel Fuel
DI	Direct Injection
EGR	Exhaust Gas Recirculation
HC	Hydrocarbon
HP	Horsepower
HRR	Heat Release Rate
D85-B10-HE5	5% HE + 10% palm oil methyl ester + 85% diesel fuel
D80-B10-HE10	10% HE + 10% palm oil methyl ester + 80% diesel fuel
D75-B10-HE15	15% HE + 10% palm oil methyl ester + 75% diesel fuel
ICE	Internal Combustion Engine
ID	Ignition Delay
IEA	International Energy Agency
LHV	Low Heating Value
LPG	Liquefied Petroleum Gas

NO_2	Nitrogen Dioxide
NO_x	Nitrogen Oxide
OH	Hydroxyl radical
O_2	Oxygen
D85-B10-PE5	5% PE+ 10% palm oil methyl ester + 85% diesel fuel
D80-B10-PE10	10% PE + 10% palm oil methyl ester + 80% diesel fuel
D75-B10-PE15	15% PE + 10% palm oil methyl ester + 75% diesel fuel
PM	Particulate matter
PME	Palm Methyl Ester
POME	Palm Oil Methyl Ester
PORIM	Palm Oil Research Institute of Malaysia
rpm	Revolutions per minute
RSM	Response Surface Methodology
SOC	Start of combustion
SOI	Start of ignition
i.e.	Introduce Example

CHAPTER 1

INTRODUCTION

1.1 Project Background

The invention of internal combustion engine (ICE) in the late 1800's was employed in the automobiles and trucks that rapidly led to the increase of the industry demand. The ICE is a heat engine where the combustion of the fuel occurs oxidizer, in combustion chamber. The main concept of ICE is the conversion chemical energy through heat energy into useful mechanical energy. There are three major types of ICE; (i) compression ignition engine (CI), (ii) spark ignition engine (SI) and (iii) gas turbines, in which each type of the engine is made with their own principle and working specifications. The CI engine that is known as the diesel engine was originally created by Rudolf Diesel in 1897 (Demirbaş 2002). In this modern world, diesel engines have manipulated major propulsion source for both inland and marine, energy used domestically for automotive transportation, heavy industry, agricultural sectors and marine transportation (Alahmer et al. 2010). Diesel engine is well known for its energy efficiency and high performance in combustion. Furthermore, a diesel engine is also known for its advantages in terms of reliability with low operating cost (Fahd et al. 2013). Other than that, it has lower fuel consumption and low carbon monoxide emissions (Imdadul et al. 2015).

Energy is the capacity of a physical system to perform work. Energy sources could be classified as renewable energy and non-renewable energy. Renewable energy is sources can be generated continuously practically without decay of sources. Examples are solar energy, wind energy, geothermal energy and hydro energy. While, non-renewable energy is sources that comes from the ground and is not replaced in a relatively short amount of time. One example non-renewable energy is fossil fuel formed by natural processes such as anaerobic decomposition of buried dead organisms. There are four types of fossil fuels; (i) petroleum, (ii) coal, (iii) natural gas and (iv) liquefied petroleum gas (LPG). These fuels contain high percentages of carbon. The industrial revolution of the 18th century in Europe distinguished the growing vast quantities of fossil fuels that were used to supply power to support the revolution (Fernihough and O'Rourke 2014). Fossil fuels or primary sources continue to be formed via natural process, which is regarded as an irreversible source, as it takes millions of years to form. According to the United States Energy Information Administration (EIA), the world's largest energy source estimation of 2017 comprises 200 quadrillion Btu of petroleum, 157 quadrillion Btu of coal, and 140 quadrillion Btu of natural gas in primary energy consumption globally (EIA, 2017). The primary energy is the energy found in nature, which contains in the raw fuel as well as other forms of energy that is received as input to the system (Wang and Nehrir 2008). There are some advantages of primary sources are abundant, affordable, cost effective and easier to produce (Ahmad et al. 2011). Coal is solid of fossil fuel that formed over millions of years by decay of land vegetation. When layers are compacted and heated over time, deposits are turned into coal. Next, fossil fuel will be extracted and process to become a diesel fuel. Some advantages of DF are, there are less knocking in the diesel engine, high efficiency, high power, and low operating cost.

However, there are some shortage beyond the advantages of DF, as it is predicted in 2070 and onward years that the world's fossil fuel reservoir would be depleted as shown in Figure 1.1 (Ballester et al. 1996, Abdullah et al. 2019). Meaning that, the world will face greater problems of limited fossil fuel production due to the fact that DF is a non-renewable and non-reusable fossil fuel production. While new technologies and investment in renewable energy should reduce our reliance on oil, its primary use as fuel means that reserves are continuing to drop. Also, the use of DF in diesel engines is most commonly known as the major pollutant contributor. Some examples of this pollution are carbon monoxide, hydrocarbon, nitrogen oxide, carbon dioxide and particulate matter emitted from diesel engines (Chen et al. 2018, Zurina et al. 2019). These emissions will cause the greenhouse effect, the production of acid rain, which is harmful to humans, plants, animals and infrastructure.

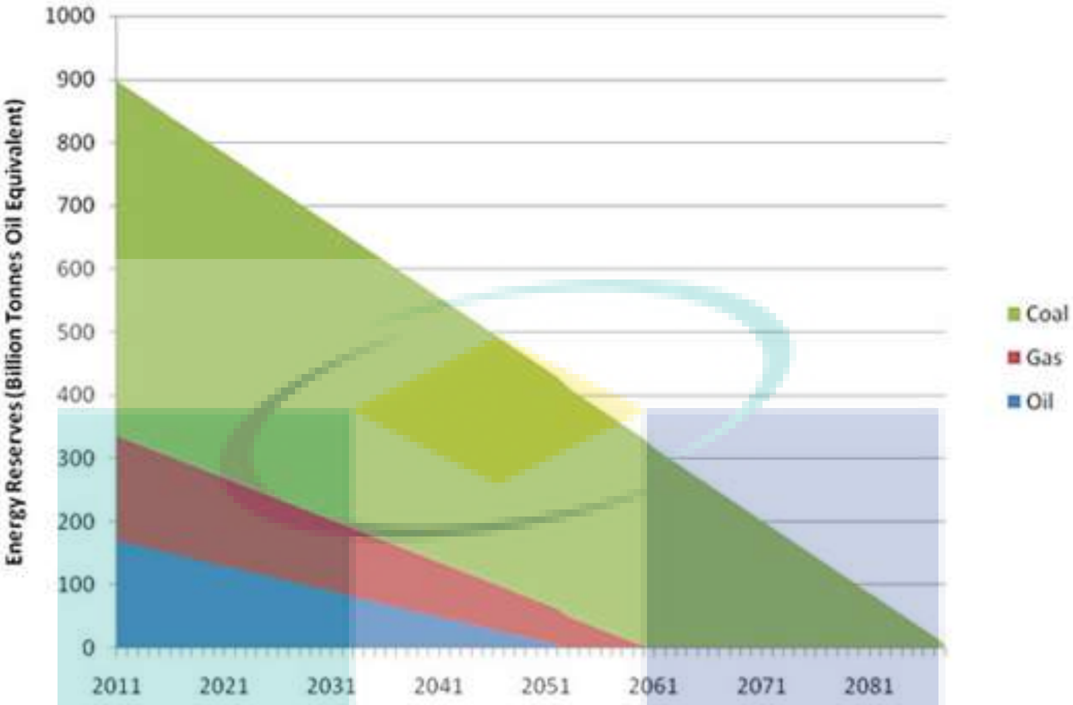


Figure 1.1 Future energy reserves

Source: Ecotricity (2016)

In order to minimize DF consumption, the most possible way to replace DF in the transportation sector is to use alternative fuels. Biofuel is one of the potential alternative fuels to solve the environmental and energy crisis in the diesel engine transport sector (Pandey et al. 2012). The term biofuel is usually used to reference liquids fuels, such as biodiesel and ethanol are used as replacements for transportation like petroleum and diesel fuel. There are two main types of biofuels; (i) biodiesel and (ii) ethanol (Naik et al. 2010). The simplest way to distinguish between the two is biodiesel is an oil and ethanol is an alcohol. Biodiesel produced by extracting naturally occurring oils from plants and seeds, while ethanol is an alcohol formed by fermentation and can be used as a replacement or additive to DF. There are four primary ways to produced biodiesel, direct use and blending, micro-emulsions, thermal cracking (pyrolysis) and trans-esterification (Ma and Hanna 1999). The most commonly used method is trans-esterification of vegetable oils and animal fats to become a biodiesel or known as methyl fatty acids or ethyl esters (Lapuerta et al. 2008). There are many types of biodiesel, such as waste cooking oils, jatropha fuel, sunflower oils, soybean oils and palm oil (Knothe et al. 2005, Van Gerpen 2005, Demirbas 2009, Ozsezen et al. 2009). However, in beginning the 1980, there was considerable discussion regarding the use of vegetable oil as a fuel rather than food. However, Bartholomew (1981) addressed the concepts of using food for fuel indicating that biodiesel should be the alternative fuel rather than vegetable oil and alcohol being the alternatives and some renewable energy must begin to take place of the non-renewable sources (Ma and Hanna 1999). In addition, Gelfand et al. (2010) have pointed out the more energetically efficient use of cropland for food in comparison to fuel production. Palm oil is one of vegetable oil that had been a controversy of 'food to fuel' production (Kasivisvanathan et al. 2012). However, to address the controversy in Figure 1.2 has been presented, biodiesel fuel demand has grown rapidly since 1990, especially the increase demand of palm oil biodiesel fuel from 13% in 1990 to 28% in 2011. Recently, palm oil became first as the most widely produced and consumed oil in the world (Thin Oil Product, 2012).

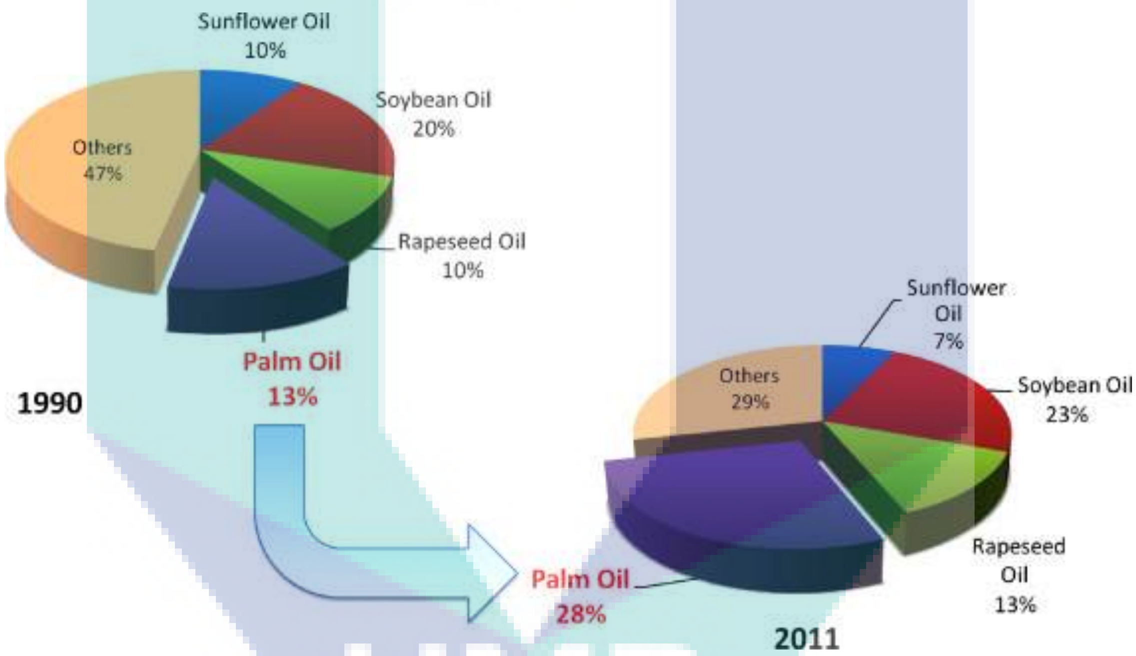


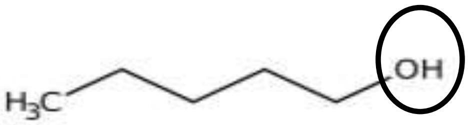
Figure 1.2 World oil and fat production
Source: Renewable and sustainable energy reviews (2013)

There are some of the advantages of palm oil is that it can be used directly in normal diesel engines without any modification, due to the similarity properties with DF. In another development, the palm oil methyl ester (POME) was successfully converted from crude palm oil through trans-esterification in 1983 by the Palm Oil Research Institute of Malaysia (PORIM, 2018). The trans-esterification shortens the molecular chain from 57 to 20, reducing the viscosity and improving the thermal stability. There are several advantages associated with POME in terms of thermo-physical properties, such as lower sulphur content (1.112 wt.%), high cetane numbers (50-52) and high flash points

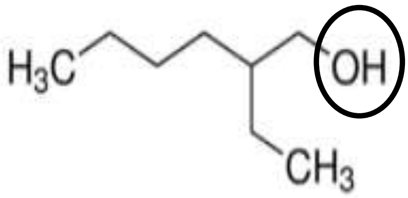
(Sivaramakrishnan and Ravikumar 2012). Also, the POME is available as a raw material for producing high oil content and large quantities of biodiesel. According to Abdullah et al. (2018), POME shows a positive impact on exhaust emissions CO that is reduced by 9.99% on 100% engine load, while brake specific fuel consumption (BSFC) is decreased by 20.83% at 25% engine load. Therefore, the POME can be considered as environmental friendly and efficient in engine performance. Vedaraman et al. (2011) studied the effect of different blends of palm biodiesel with DF on engine performance and emission characteristics and found B20 to be the optimum blend in term of higher thermal efficiency and lower NOx compared to DF. Fattah et al. (2014) tested the effect of antioxidant (BHA and BHT) on the performance and emission characteristics of a diesel engine fuelled with palm biodiesel blends with constant 20% palm methyl ester (PME). At first, these authors found that BSFC of B20 produced higher by 4.71% compared DF, due to attributed to the volumetric effect of the constant fuel injection rate together with higher viscosity. However, when the addition of BHA and BHT to B20, resulted in reduction in BSFC of 0.64% and 0.18% respectively. Moreover, the B100 produces higher NOx and produced low brake power due to the presence of oxygen. Also, the thermo-physical properties such as higher viscosity, higher molecular weight, lower volatility and high flash point compared to DF, cause poor atomization and lead to incomplete combustion (Sivalakshmi and Balusamy 2013). Therefore, the author presented the test results of B20 with additive BHA and BHT to overcome the problems.

Previous researchers have found that the B100 is composed of higher viscosity resulting in a poor atomization and incomplete combustion, so to convene up the most desired performance levels used fuel additive to improve the quality of biodiesel and DF. Therefore, the fuel additives will help out biodiesel properties to recover its engine combustion, performance and emission environmental standard. The fuel additive selection will be based upon the drawbacks of biodiesel such as density, viscosity, additives solubility, cetane number during blending process and running experiment. In addition, the concentration of fuel additives is not regulated. The flexible concentration fuel additives are because to control; (i) shrinking harmful emission from fuel combustion, (ii) developing the combustion and performance properties of fuel and, (iii) protecting the fuel tank, pipeline and other massively expensive corrosion. Some example of fuels additive is nanoparticles (aluminium oxide, titanium oxide, carbon nanotubes, etc.) (Venu and Madhavan 2016, Adzmi et al. 2019), and alcohols (methanol and ethanol) (de Menezes et al. 2006, Yasin et al. 2014). As such, there has been many researches involving the production of alternative fuels by blending these fuel additives into biodiesel and DF (Sayin 2010, Muralidharan and Vasudevan 2011, Selvaganapthy et al. 2013).

The most important additive for diesel fuel is oxygenated additives, due to the complete combustion are requires oxygen, fuel and heat to get burned. The fuels containing oxygen and mixture components should contain at least one oxygen atom by molecules on the side of carbon and hydrogen atoms (Kumar et al. 2018). As such, the additional of oxygenated additives combined with DF or biodiesel must be able to mix with any ratio without have two-phase separation. Therefore, by adding a sufficient oxygenated additive in DF and biodiesel, the cetane number contents in oxygenated additives should be presented and, the cetane number must increase during the mixture. The aid of the oxygen is to promote fuel combustion without emitting large amounts of inert nitrogen into the air, which causes harmful substances, such as NO_x emission in some operating engine load conditions of the CI diesel engine. The commonly used oxygenated additives, like alcohol are very useful for developing the combustion process and octane enhancers. In fact, alcohol receives more attention in ICE as it has been used as fuel improvement and substitution fossil fuel to DF in CI engines (Rakopoulos et al. 2013). Alcohol is divided into two categories, namely; (i) short-chain alcohol, and (ii) long-chain alcohol. The carbon atom (s) with less than five carbon atoms are known as short-chain alcohols, while the carbon atoms with more than five carbon atoms are known as long-chain alcohols. The most commonly used alcohols as oxygenators, are long-chain alcohols, such as pentanol, hexanol, heptanol, octanol, nonanol and decanol as shown in Figure 1.3. Long-chain alcohols are capable of minimizing the ignition temperature of biodiesel and reducing the exhaust emissions observed in the diesel engine. On the other hand, long-chain alcohols have high energy density, high cetane numbers, high viscosity, high flash points and boiling points compared to short-chain alcohols (Campos-Fernández et al. 2012, Atmanlı et al. 2013, Emiroğlu and Şen 2018).



1-Pentanol



2-ethyl-1-hexanol

Figure 1.3 Long-chain alcohol

The short-chain alcohol, such as methanol, ethanol, and propanol are well known for its characteristics as oxygenated liquid that could increase oxygen content during combustion and reduce smoke emission (Banapurmath et al. 2015). Rashedul et al. (2014) reported that mixing of n-butanol with DF, resulting in a reduction of BSFC by 6.25%, while BTE increased by 5.81% compared to DF. However, the reduction of BSFC due to the authors indicated that the application of platinum as a fuel additive able to stabilize the bonding of n-butanol-diesel fuel blends. This is because the addition of n-butanol-diesel have mixed phase separation problems. Moreover, there are more deficiency of short-chain alcohol, which are low calorific value, as well as low cetane numbers that have issues on miscibility and stability, weak auto ignition quality and improper lubricating behaviour limiting the use in DF. Other than that, Doğan (2011) also revealed the n-butanol-diesel fuel blends which increased NO_x by 31.57% compared to DF at 3.3 N.m engine load. In addition, short-chain alcohol was less efficient in BTE due to the phase separation problems of ethanol-diesel fuel blends research by Taghizadeh-Alisaraei and Rezaei-Asl (2016). Moreover, the authors stated by increasing the concentration of ethanol, it caused the ignition delay by 45.67% and increased the in-cylinder pressure by 70.91%.

Likewise, in order to overcome the weakness of short-chain alcohol, long-chain alcohol have the potential to be selective fuel additive which blended with DF or biodiesel. Recently, long-chain alcohol has gathered the attention of researchers for fuel additive use in diesel fuel, due to its advantages over short-chain alcohol. One of the most advantages is, the utilization of long-chain alcohol that is enriched with oxygen content can improve thermo-physical properties, such as density, cetane number, flash point, viscosity and boiling point. Moreover, long-chain alcohol-diesel fuel blends shows no phase separation and can normally run without any additional fuel additive to avoid phase separation. Pentanol and hexanol are examples for long-chain alcohol that consists of five and six carbon atoms respectively in the parents' chain.

Based on the description above, the present research employs the long-chain alcohol-biodiesel-diesel tri-fuel blends as a new alternative fuel. In order to fill up the gap, 5%, 10% and 15% volume ratio of 1-pentanol (PE) and 2-ethyl-1-hexanol (HE) concentration are blended with remaining 10% constant volume ratio of B100 and 85%, 80% and 75% of DF to produce tri-fuel blends in this research. Additionally, the fuel blending process is carried out using ultrasonic emulsifiers (Hielscher UP400S) with an amplitude of 70%, and 0.5 cycles with a duration of 2 minutes. In this experiment, natural aspirated YANMAR TF120M single cylinder, direct injection diesel engine is also employed. The experiment is performed at a constant engine speed 1800 rpm with various engine loads of 0%, 25%, 50%, 75% and 100% for DF, B100, D85-B10-PE5, D80-B10-PE10, D75-B10-PE15, D85-B10-HE5, D80-B10-HE10, and D75-B10-HE15. The analysis of the results will be used to investigate on the combustion characteristics, engine performances and exhaust emissions of the tri-fuel blends. The combustion characteristics contain of in-cylinder pressure and heat release rate (HRR), while the engine performances comprise brake specific fuel consumption (BSFC), brake thermal efficiency (BTE), brake power and torque. The exhaust emissions include carbon monoxide (CO), carbon dioxide (CO_2) and nitrogen oxide (NO_x). Finally, the response surface modelling (RSM) is developed based on standard back-propagation algorithm standard for validating the output parameter.

1.2 Problems statement

There has been an increasing excessive energy demand over the time as a result of the rapid economic development, in which diesel engines has been the largest contributor to the total consumption for DF, due to the fact that it has lower CO emission, higher reliability on combustion and performance. Despite these advantages, there are disadvantages which are seen to be present in the use of DF, such as the depletion of fossil fuels, acting as a major contributor to pollutants and harmful impacts to human beings. DF is produced from fossil fuels, and there has been prediction that the world's fossil fuel reserves very limited stock. Moreover, fossil fuels are non-renewable and non-reusable source, which means there will be some major problems that will be faced due to the limitation of fossil fuels to produce more DF (Hasannuddin et al. 2016). Furthermore, excessive emissions that lead to pollution and natural disasters such as CO, CO_2, NO_x and particulate matter (PM) are result of diesel engines. Also, the effect of CO exhaust gas contributes to a hazardous respiratory system, which could harm human lung even at the smallest part of alveoli. Additionally, CO and CO_2 emissions emitted by the DF combustion will form the greenhouse effects, thinning the ozone layer, and contribute to global warming. The release of NO_x emissions also contributes to the formation of acid rain, which harm humans, animals, plants, and even damaging infrastructure. According to Labeckas and Slavinskas (2006), some health problems occur due to exhaust emissions from fuel combustion, such as asthma, and lung cancer.

In order to addressed the shortage of DF, new formulation of biodiesel was found from previous research. There some of biodiesel that found by Muralidharan and Vasudevan (2011), that used waste cooking oil as biodiesel. The author blended 20%, 40%, 60% and 80% of biodiesel with DF, with improvement in BTE and BSFC. Unfortunately, there are some disadvantages, which is high peak pressure and longer the ignition delay, thus increase the NO_x emissions. This is because, when peak pressure increases, the in-cylinder temperature increase, that leading to increase the NO_x emissions. In addition, Imdadul et al. (2016) was blended DF with 10%, 15% and 20% of *Calophyllum inophyllum* (CI). The author also found that the peak pressure was increased, that cause the start of combustion delayed, increasing the in-cylinder temperature thus increasing the NO_x emission. Therefore, in this research biodiesel from palm oil methyl ester (POME) was selected to substitute and minimize the usage of D, as new alternative fuel.

Nowadays, alcohol is one of additives that is very attractive to many researchers, as an addition to DF or biodiesel. This is because adding alcohol in DF or biodiesel will create a new formulation of alternative fuel (Demirbaş 2003, Sukjit et al. 2012, Kremer et al. 2015, Sánchez et al. 2015). However, Kumar et al. (2003) have previously only focused on short-chain alcohols, like methanol, ethanol and butanol, known as oxygenated fuel that increase the availability of oxygen during combustion. In spite of this, short-chain alcohols have low calorific values, cetane numbers and heating values. Other than that, the main concern for short-chain alcohols is low miscibility with DF and biodiesel.

Therefore, long-chain alcohols will be blended with POME and DF to create a new formulation as long-chain alcohol-biodiesel-diesel tri-fuel blends in the present research. It is expected that the best result analysis must show better combustion, engine performance and emission as well as economy performance among all the fuels. For example, low values of BSFC are obviously desirable, and reduction of exhaust emission in diesel engines. Accordingly, there are some results found by Muralidharan and Vasudevan (2011) in performance, emission and combustion characteristics by using biodiesel (sunflower oil) blend with DF in 20%, 40%, 60% and 80% volume concentration of biodiesel. As such, they stated that B40 shows the best improvement in engine performance due to the reduced BSFC and increased BTE by 17.52% and 31.48%, respectively, compared to DF. This is because of the decrease in calorific value of B40. On the other hand, Wei et al. (2014) investigated the effect of n-pentanol addition on the combustion, performance and emission in diesel engine fuelled with DF. The addition of n-pentanol in DF, resulted in the HC and PM emission reduction by 30% and 17.14% in 10% n-pentanol (DP10) at 7.10 bar engine load. This is due to the oxygen content of blended fuel increase as n-pentanol is added, which favours the oxidation of unburned HC at relatively high in-cylinder temperature. Moreover, Zhang and Balasubramanian (2016) conducted a study to make a comparative evaluation of the effects of blending n-butanol and n-pentanol with biodiesel at 10% and 20% by volume on engine performance. The engine performance showed butanol and pentanol-biodiesel blends which lead to a maximum increase by 1.5% and 1.6% in BTE, due to the addition of butanol and pentanol to biodiesel that can result in the oxygen enrichment, higher flame speed and improve spray characteristics. Although, despite the availability of many researches carried out on long-chain alcohol-diesel fuel blend combustion analysis, none of them investigated for the 5% long-chain alcohol volume ratio. In addition, there has not been any research that blended all three solutions long-chain alcohol-biodiesel-diesel tri-fuel blends. Preliminary review of previous literature in the present study shows that there has not been any experiment involving the usage of tri-fuel of (long-chain alcohol + biodiesel + DF). The long-chain alcohol comprising of PE and HE, biodiesel from POME and DF from JIS#2. The PE and HE has various volume ratio, which is 5%, 10% and 15% each of long-chain alcohol. While constant volume ratio for POME by 10%, due to concern the performance, and the differences in oxygen content of long-chain alcohol in tri-fuel blends, next DF fulfil the rest of 100% of blending ratio. Hence, the tri-fuel blends imperative to highlight the need for the current research.

Obviously in this research going to make constant volume ratio of B100 with 10%, due to minimize the formation of NO_x and increased the performance efficiency. Other than that, by adding some fuel additive for balanced the thermo-physical properties of B100, thus getting better combustion. In addition, the constant volume ratio of B100, going to determine the efficiency of various volume ratio of additive (long-chain alcohol) in this tri-fuel blends, rather than various of B100.

1.3 The objectives of research

The overall objectives of this research are to analyse the new formulation of long chain alcohol-biodiesel-diesel tri-fuel blends to meet new alternative fuel demands in the future. As such, the specific objective of the present research will be based on the following aspects:

a) To determine the stability and thermo-physical properties of D85-B10-PE5, D80-B10-PE10, D75-B10-PE15, D85-B10-HE5, D80-B10-HE10 and D75-B10-HE15.

b) To investigate the combustion characteristics, engine performances and exhaust emissions of long-chain alcohol-biodiesel-diesel tri-fuel blends.

c) To determine optimum blend ratio of D85-B10-PE5, D80-B10-PE10, D75-B10-PE15, D85-B10-HE5, D80-B10-HE10 and D75-B10-HE15 based on engine performances by using Response Surface Methodology (RSM) software.

1.4 Scope of research

The scope of this research involves tri-fuel blends preparations and experimental work on sample fuels, in which this detailed will be implemented in the following scope in order to achieve the objectives of this research:

i. Perform blending process of long-chain alcohol-biodiesel-diesel tri-fuel blends (85%, 80% and 75% of DF) + 10% constant POME + (5%, 10% and 15% each of PE and HE) blending ratio for tri-fuel blends D85-B10-PE5, D80-B10-PE10, D75-B10-PE15, D85-B10-HE5, D80-B10-HE10 and D75-B10-HE15 respectively by using ultrasonic emulsifier.

ii. Observed the stability based on the sedimentation scale and conduct the laboratory of thermo-physical properties of a tri-fuel blends, such as calorific value, cetane number, density, dynamic viscosity, and kinematic viscosity.

iii. Conduct an experiment on single cylinder diesel engine with various engine loads 0%, 25%, 50%, 75% and 100% at constant engine load 1800 rpm, due to optimum better engine performances.

iv. Data collections of tri-fuel blends for combustion characteristics (in-cylinder pressure and heat release rate), engine performances (BSFC, BTE, brake power and brake torque) and exhaust emissions (CO, CO_2 and NO_x) on diesel engine.

v. Analyse the data collection, verification and conclude.

vi. Build up historical data to find the optimum blend ratio of tri-fuel blends by using RSM software.

1.5 Thesis outline

This thesis outline consists of five chapters including this chapter. The contents of each chapter are described as follows:

Chapter 1 introduces a general description of the field concern. In this chapter involved of an introduction, problem statement, the objectives of research, scope of research and thesis outline.

Chapter 2 reviews has been written previously. This chapter consists of literature reviews, backgrounds and other research in the same area and related issues to running the diesel engine. In addition, in this chapter, the emphasis on new formulation alternative fuel, the type of biodiesel used and the additive fuel. Moreover, discuss the research gap of this research compared to other research.

Chapter 3 presents the methods and parameters of this research. Suggest the best process and improve the methodology of material and equipment. Details of blending process of tri-fuel blends and preparation engine diesel are explained in this chapter.

Chapter 4 presents the experimental results and finding the research. The overall data describes the details in this chapter which comprise of thermo-physical properties, combustion characteristics, engine performance, and exhaust emissions in diesel engine. Presents the appropriate tables and figures to support all results and make it clearer.

Chapter 5 interprets the limitation of research and present any recommendations for future research. Generate conclusion of research and answered all the problem statements.

CHAPTER 2

LITERATURE REVIEW

2.1 Diesel engine

The power behind larger engines, such as trucks, trains, ships and submarines are diesel engine. This type of engine operates in accordance with the principle ICE where fuel is burned in the main part of the engine (the cylinder) and power generated. As per four-stroke engine, the cylinder needs two revolutions of the crankshaft to produce one power stroke to complete the working cycle. A complete work cycle requires the intake, compression, power or combustion and exhaust stroke, respectively. Stroke is the distance at which the piston moves up and down inside the cylinder. Figure 2.1 shows how four-stroke engine diesel work. Firstly, in the intake stroke, the piston initially moves from top position or top dead centre (TDC) to lowest position or bottom dead centre (BDC), in which the intake valve will open and together DF with the air enters into the cylinder and thus closed exhaust valve. Once the air and DF enter the cylinder, the intake valve is closed. During the compression stroke, both intake and exhaust valves are closed and the piston moves upwards and compresses the air-fuel mixture. Conversely, the compression air reaches approximately 700-800°C (Heywood, 1988). As such, the explosion creates a powerful force that drives the piston downwards to undergo in combustion stroke. The last part of the cycle is the exhaust stroke, in which when the piston moves downwards, the exhaust valve opens and the exhaust gas leaves the cylinder. In all, all stroke will end and the engine is ready for the next cycle, thus intakes another charge of air and fuel again. The advantage of the four-stroke engine cylinder is lower fuel consumption, and high fuel compression.

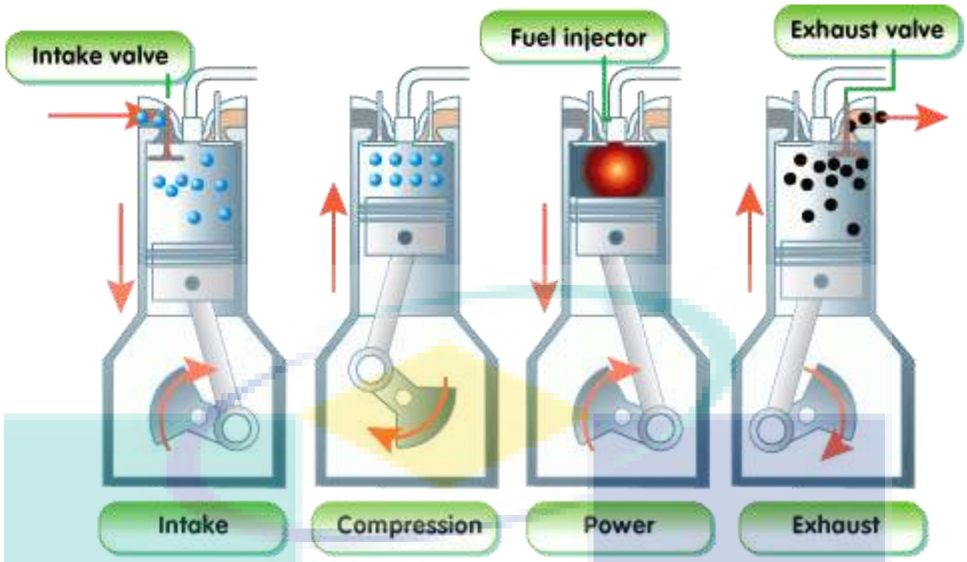


Figure 2.1 The process of four stroke cycle diesel engine
Source: The secrets of science (2014)

2.2 Biodiesel

The excessiveness of diesel engines used worldwide is rapidly contributing to the rigorous emission regulations and raise concern over energy security increase, and hence interest researchers on new formulation of alternative fuels (Scarpete 2013). The initiative of finding an alternative fuel, biodegradable and environmentally-friendly fuel to meet the energy demand has been discussed in recent era. This is because, biodiesel has been seen as one of the alternative fuels that possess the potentials of replacing DF owning to its renewability and better fuel properties than DF. Researchers have concentrated on biodiesel capabilities to address pollution problems and energy demands of the future generation (Ashraful et al. 2014, Ellabban et al. 2014, Altaie et al. 2015). Interestingly, the usage of biodiesel is a derivative of woods, plants, leaves, biomass and animal waste. Over the years, there has been many alternative fuels reported to substitute DF, such as insect oil, waste cooking oil, alcohol-diesel fuel, emulsion fuel and palm oil-diesel (Utlu and Koçak 2008, Ozsezen et al. 2009, Campos-Fernández et al. 2012, Ithnin et al. 2015, Kamarulzaman et al. 2018).

In another development, palm oil produced from palm plants can be used to make biodiesel for internal combustion engines. Thus, it is seen as a way of reducing the impact of the greenhouse effect and way of diversifying energy supplies to assist national energy security plans. Based on the reviews made by Ozsezen et al. (2009), the production of smoke opacity, CO, and HC emissions were reduced by 47.96%, 9.52% and 72.68%, respectively, compared to DF when running the diesel engine fuelled with palm and canola oil methyl ester. These changes occurred, although the air-fuel equivalence ratio decreased, due to a BSFC increase of 269.88g/kW-h when the canola oil was used. Previous studies by Abdullah et al. (2015), analysed the effect of POME on fuel consumption and exhaust emissions of diesel engine operating with blended fuel DF with jatropha oil methyl ester (JOME). These researchers pointed out that a JOME biodiesel has resulted in the increase of BSFC and higher NO_x emission. The most miraculous thing that happened with the addition of POME onto (DF + JOME with 5%, 10% and 15% of volume ratio) led to a significant improvement in BSFC, decreased total hydrocarbon (THC), CO and NO_x emissions. In the same vein, the emission of NO_x and CO were reduced by 14% and 25% respectively for 15% POME, due to the increases of the ignition delay and a higher oxidation process at higher combustion temperatures. In contrary, for other types of biodiesel Buyukkaya (2010) reported the effects of biodiesel on a DI diesel engine performance, emission and combustion characteristics on 5%, 20% and 70% of rapeseed oil blends with DF. These researchers found that BSFC of B5, B20 and B70 were higher by 2.5%, 3.0% and 5.5%, respectively compared to DF, due to the lower heating value of biodiesel. Furthermore, the majority of researchers have reported that when running biodiesel in a diesel engine, the BSFC increases with the increase in proportion of biodiesel content in the blends, thus resulting in the reduction of the fuel blend heating values (Ramadhas et al. 2004, Zheng et al. 2008). However, the advantage of POME is that POME could reduce the formation of exhaust emission PM due to biodiesel that is an oxygenated agent and have no sulphur. The review by Ali (2011) reported that biodiesel became the best fuel for DF substitute since burning biodiesel produced lowest greenhouse emissions to surrounding.

In fact, the main advantages of biodiesel, such as POME are that they are renewable sources, safe to be used in all conventional diesel engines, efficient in engine performance and engine durability. Other than that, POME is non-flammable, non-toxic, minimizes the production of emissions of less visible and non-hazardous smoke. Therefore, POME significantly enhances the economic viability of biodiesel production, thus make the environment-friendly, even when it has yet to achieve zero emissions (Gumus and Kasifoglu 2010).

2.3 Additive fuels

Biofuel is an alternative fuel suitable for diesel engines. It is made from 100% purity or by adding fuel additive that is blended with DF. Additive fuel is a formulated compound to improve the quality and efficiency of fuel engine performance in diesel engines. Fuel additives are substances available in liquids and powders. The fuel additive works in different ways and claims to have various characteristics on fuel, such as improving the combustion, improving cetane, controlling soot and remove sludge. Additionally, fuel additives are claimed to enhance the proper lubrication of the working components, thus particularly benefits to less wear and tear on the moving parts. Examples of fuel additives are surfactants, such as tween and span, nanoparticles, like aluminium oxide (Al_2O_3) and carbon nanotubes (CNT), organic germanium and alcohols such as methanol, ethanol and butanol (Liu et al. 2007, Sajith et al. 2010, Syafiq et al. 2017, Chen et al. 2018, Abdullah et al. 2019). Furthermore, in the study of performance of a single cylinder, the DI diesel engine that uses water fuel emulsion investigated by Abu-Zaid (2004) reported that brake thermal efficiency increased by 3.5% for 20% of water emulsion (20% water and 80% diesel with surfactant). The result was agreed upon by Ganesan and Ramesh (2002) , who found that the emulsion resulted in a BTE efficiency increase by 3.0% compared to DF. Emulsion fuels consist of DF, distilled water and additive fuel span (80) and tween (80) with 2% by volume surfactants. More so, Syafiq et al. (2017) observed performance and exhaust emission analysis using diesel-organic germanium fuel blends. The emission results indicated that CO_2 and NO_x decreased by 2.1% and 17.7% respectively compared to DF. Conversely, additive nanoparticles such as AL_2O_3, CNT and silicon oxide (SiO_2) were investigated by Chen et al. (2018). The authors concluded that BTE increased by 15.4%, which is achieved from 25ppm and 0.88% that reduces CO_2 for all engine loads SiO_2-diesel fuel blend. Other than that, CNT-diesel fuel blends improved BSFC by 19.85% due to higher calorific value of fuel blends and decreased BTE by 18.8% for DC50 (50ppm of CNT) due to shorter ignition delay, thus promoting a more complete combustion. Lastly, alcohol fuel additive consists of two types; (i) short-chain alcohol, and (ii) long-chain alcohol. Likewise, the study carried out by De Poures et al. (2017) showed a reduction of NO_x by 41% in emission test of 30% concentrations of hexanol. Similarly, a results has been agreed by Kumar and Saravanan (2016), of a reduction by 42% of NO_x emission at the retarded injection timing of 21°CA bTDC.

2.3.1 Short-chain alcohol

Alcohol is an organic compound where the hydroxyl functional group (-OH) is bound to a saturated carbon atom. Short-chain alcohol consists of fewer than three carbon atoms (methanol, ethanol and propanol). Short-chain alcohols are also known as an oxygenated liquid that could improve the oxygen content in fuel, thus making it to perform better during combustion and simultaneously reduce exhaust emissions (Banapurmath et al. 2015). Ethanol is one of short-chain alcohol additive fuel that acts as an attractive alternative fuel due to the renewable bio-based and acts as oxygenated agent to provide the potential for reducing particle emissions in the compression ignition diesel engine. Aside that, the advantage of short-chain alcohol-diesel can be used in diesel engines without any modification. In another study, the effect of adding EN (2-ethylhexyl nitrate) to the diesel-ethanol blends on the diesel engine performance and emission was described by Ciniviz et al. (2017), where it was seen that the CO, CO_2, and NO_x emissions of ethanol was decreased by 7.93%, 20.22%, and 15.87% respectively compared to DF. In the case when ethanol emits less of emission than DF, it is revealed that EN would cause the cetane number to be slightly increased, as well decreasing the kinematic viscosity, lowering heating values and increasing density.

On the contrary, previous studies indicated that short-chain alcohols are mainly limited due to their low calorific value, low cetane index, poor blending solubility and long ignition delay (Klusmeier et al. 1985, Kremer et al. 2015). Also, most studies have reported that short-chain alcohols vaporize very fast and have low miscibility when blended with DF as opposed to long-chain alcohol, especially at lower temperature (Rakopoulos et al. 2011). Conversely, the addition of ethanol to DF can reduce lubrication, add wear and tear problems in the design of sensitive fuel pump. In another study, Li et al. (2005) reported that ethanol possesses lower viscosity and calorific value, with some imposing minor changes to the fuel delivery system to achieve the maximum engine power. In the same vein, high concentration ethanol-diesel blends have been studied by Meiring et al. (1983), where it was reported that ethanol possess a significant low cetane number, which reduced the cetane number of the ethanol-diesel blends. Moreover, ethanol has a lower flash point compared to DF and higher vapour formation in confined space, thereby requiring extra precautionary during handling (Hansen et al. 2005).

2.3.2 Long-chain alcohol

The disadvantages of short-chain alcohol can be replaced with long-chain alcohols, which is on par with diesel fuel. Carbon atoms with more than four carbon atoms are known as long-chain alcohols. The long-chain alcohol can act as properties of oxygenated liquid consisting of high calorific values, cetane numbers and better miscibility when blended into diesel fuel. The varieties of long-chain alcohols, such as butanol, pentanol, as well as hexanol are blended with DF to form long-chain alcohol-diesel fuel blends, thereby increases the oxygen content, perform better combustion and reduce emissions. Kumar et al. (2018) stated that the oxygen elements help supports combustion of fuel without emitting any high amount of inert gasses, such as nitrogen gas into the air and causing harmful substances as NO_x emissions. This fuel can be employed as a total replacement or blends with DF to operate in the CI engine. There are also some varied success elements with alcohol additives that have been reported either on properties, combustions, engine performances, or emissions compared to their diesel counterparts (Kim and Choi 2008, Arbab et al. 2013).

Pentanol is a carbon chain that consists of 5 carbon atoms that has potential as a blending component with DF owing to its higher energy density, higher cetane number, better blend stability and less hygroscopic nature compared to short-chain alcohol (Saravanan 2015). In addition, the latent heat of vaporization, density and viscosity of pentanol close to DF properties. Pentanol is an excellent renewable alternative, that can be produced from biological pathways like natural microbial fermentation of engineered microorganisms (Cann and Liao 2010) and biosynthesis from glucose (Zhang et al. 2008). Saravanan (2015) was investigated 10%, 20%, 30% and 45% volume ratio pentanol-diesel blends effect of exhaust gas recirculation (EGR) on performance and emission, were resulted in solubility of pentanol-diesel was tested and no phase separation was found after 48 hours. In addition, the authors found NO_x emissions were reduced by 57% and 30% for PEN45 (45% pentanol + 55% DF) for load 2.6 bar and 5.3 bar respectively. Previous study by Abdullah et al. (2018), reported on effect of pentanol-diesel fuel blends on thermo-physical properties and engine performance. The authors stated on thermo-physical show density and viscosity were reduced by 1.2% and 12% for PE20 (20% of 1-pentanol + 80% of DF) compared to DF. At 25% engine load BSFC was reduced and BTE increased by 20.83% and 11.2% respectively compared to DF for PE5 (5% of 1-pentanol + 95% of DF). The reduction BSFC is due to the increase of diffusion rates of the fuel vapour inside the combustion chamber, which promotes air-fuel mixture preparation before ignite. Moreover, Li et al. (2015) reported the combustion and emission of diesel engine fuelled with diesel/biodiesel/pentanol fuel blends. The authors found the combustion parameter in ignition delays of fuels do not show much difference in spite of the different cetane number at the main combustion phase. The combustion duration is shortened as the pentanol addition to blends owning to the improved fuel-air mixing rate, and also pentanol blended fuel have rapid combustion rate. Authors also stated that, the addition of pentanol reduced NO_x emissions for D70P30 (70% of DF + 30% 1-pentanol) for 8% compared to DF. This is due to pentanol has higher latent heat of vaporization, leading to lower combustion temperature which contributed to the reduction of NO_x formation. (Li et al. 2015, Atmanli 2016, Babu and Anand 2017, Yilmaz and Atmanli 2017) has concluded that the potential of adding pentanol to different diesel or biodiesel blended fuel in order to improve the overall fuel performance, thus attain an overall good engine performance and combustion. On one hand, the additional of pentanol with lower viscosity and high volatility could improve the atomization quality of diesel or biodiesel blends, and the higher oxygen content in pentanol could reduce soot emission. On the other hand, biodiesel has higher cetane number could maintain the ignition quality for the blended fuel. Therefore, a promising multi-component blending strategy is determined to attain the higher percentage of oxygen content, but at the same time keeping important fuel properties such as density, viscosity, volatility and cetane number within acceptable limits. Imdadul et al. (2016) has been proven in previous statements, where they investigated the performance, emission and combustion of a light duty diesel engine fuelled by DF and *Calophyllum inophyllum* (CI) biodiesel with addition of pentanol (10%, 15% and 20% by volume). The results show an increasing proportion of pentanol in biodiesel blends reduced the density and viscosity by 2.4% and 10% respectively, due to presence pentanol decreased viscosity of the fuel blends owing to its better atomization efficiency. The authors found the fuel blends reduced the BSFC on average of 8.7% compared to DF. This is due to the effectiveness of higher ignition as a result of the higher oxygen content as well as lower density and viscosity of pentanol. While, the BTE and brake power values of the fuel blends indicated better combustion efficiency by 15% and 10.4% for C20P20 (20% of *Calophyllum inophyllum* + 20% of pentanol + 60% of DF).

Another potential long-chain alcohol that have an attractive by researcher is hexanol. Hexanol is obtained by anaerobic fermentation of lignocellusic biomass such as rice straw, corn stalks and sugarcane bagasse, and wood-pulp without much reliance on food crops. In addition, hexanol produced industrially by the oligomerization of ethylalcohol from agricultural food and beverage processing (Raj and Saravanan 2011). Therefore, the producing hexanol are not having a controversy of "food to fuel", and the sources of produces hexanol are renewable, reusable and non-limited stock. Two additional straight-chain isomers of 1–hexanol, 2-hexanol and 3-hexanol exits, both of which differing by the location of the hydroxyl group (Karabektas and Hosoz 2009, Campos-Fernandez et al. 2013, Murcak et al. 2013). Usually researchers used 2-ethyl-1-hexanol for experiment with molecular formula ($C_8H_{17}OH$). Blending of oxygenated agents like hexanol with biodiesel and DF, will populate fuel-rich regions with hydroxyl group radicals that can catalyze unsaturated HC (hydrocarbon) species to be oxidized (Park et al. 2011). Hexanol is slightly soluble in water but miscible with diethyl ester and ethanol (De Poures et al. 2017).The others possible reason for choosing hexanol as an alcohol is due to hexanol consist 6 carbon straight-chain alcohol that has great potential as a blending component with DF owning to its higher cetane number, lower viscosity and high energy content compared to short-chain alcohol. Pandian et al. (2018) has studies the 10% and 20% volume of hexanol blended with cashew nut shell biodiesel on emission and performance. The author stated that BSFC for CNSBD90H10 and CNSBD80H20 was 0.00752 kg/kWh and 0.01484 kg/kWh respectively lower than CNSBD100. This is because the increasing of hexanol content and increase in energy density of fuel. In addition, the reduction in viscosity of fuel with the additional of hexanol, where low viscosity assists the combustion process as it combines the fuel with air. Meanwhile, (Raj and Saravanan 2011) explored the influence of hexanol-diesel blends on constant speed diesel engine by 10%, 20%, 30%, 40% and 50% volume ratio of hexanol. These studies revealed the brake thermal efficiency (BTE) of 10% hexanol blends higher by 33.9% efficiency compared to DF. This can be attributed to the higher premixed combustion part possessed by the hexanol blends due to lower cetane number of hexanol, and lower heat losses and leaner combustion. There are many types of hexanol, but commonly used hexanol is 2-ethyl 1-hexanol (2-EH) (Suhaimi et al. 2018). The use of hexanol in diesel engines was found rarely and investigated within five years ago. One of the authors very recently is Suhaimi et al. (2018) who analysis of combustion characteristics, engine performance of 2-EH (5%, 10% and 20% by volume). The authors stated the peak pressure for HE20 (20% of hexanol + 80% of DF) is higher by 2.99% compared to DF, due to high cetane number and lower viscosity of 2-EH, which increase fuel-air mixing ratio. They also found the BSFC was reduced by 45.22%, 2.68% and 8.11% for HE5, HE10 and HE20 respectively compared to DF, due to low calorific value and low energy density of 2-EH. Moreover, studied by Abdullah et al. (2019) was investigated the impact of diesel-biodiesel hexanol tri-fuel blends on combustion and emission of a diesel engine. Authors was added 5%, 10% and 15% of hexanol to DF and resulted the peak pressure for B100, HE5, HE10 and HE15 were reduced by 6.14%,1.99%, 1.38% and 0.002% compared to DF. The results can be explained by the presence of hexanol enriched in an oxygen content carrying a strong premixed combustion phase.

2.4 Thermo-physical properties

The required thermo-physical properties of fuel blends are calorific values, cetane numbers, density, dynamic viscosity and kinematic viscosity. The test of thermo-physical properties is to indicate the quality of the fuel during the combustion process. Other than that, the behaviour of combustion characteristics, engine performance, and exhaust emissions of a tri-fuel blends are also directly related to thermo-physical properties. The American Society for Testing and Material (ASTM) is the organization that develops international voluntary consensus standards (Marpet 1998).

2.4.1 Calorific Value (CV)

The calorific value (CV) is the amount of heat released by a unit volume of substance during complete combustion and indicates the energy in the fuel (Heywood). The heat generated in kilojoules when 1 gram of fuel is completely burned. The unit that represents the calorific value is MJ/kg, and the value of CV is directly proportional to the heat generated. When CV increases, more heat is produced during combustion, thereby increasing the behaviour of the fuel. Moreover, the higher calorific value can be found in tri-fuel blends, thus leading for better combustion and atomization. This is because, the biodiesel commonly consists of low calorific value, but long-chain alcohol consists of high calorific value compared to biodiesel. Therefore, a promising multi-component blending strategy is determined to attain the higher calorific value. As stated by Phan and Phan (2008), the increase in percentage waste cooking oil (WCO) biodiesel is as a result of a reduction in CV. The same finding has been reported by Zhang and Balasubramanian (2016), who found that BTE was increased by 1.5% compared to biodiesel at low engine load. Conversely, the improvements of BTE are caused by a pentanol consisting of oxygen, higher flame speed resulting in lower CV when increased the concentration of alcohol. In addition, the formation NO_x emissions generally formed in the high combustion temperature, but the significantly lower level of formation NO_x emission during the combustion, is due to low calorific value.

2.4.2 Cetane Number (CN)

The cetane number (CN) is one of the physical properties that measure the prime indicator of fuel quality in the combustion chamber of a diesel engine which can easily ignite the fuel (Bamgboye and Hansen 2008). The CN rating of the fuel determines to a great extent and has the ability to start the engine at low temperatures and provide smooth warm up as well as even during the combustion phase. The DF rating cetane number is around 40-55 (Heywood). More so, the higher the CN, the easier the fuel ignition. Also, the CN of a DF is related to the ignition delay period, the time elapsed between injection of fuel into the cylinder and the start of ignition. In particular, high CN will shorten the ignition delay period, therefore an adequate of CN leading the efficient in engine performance. Both reference compounds on the scale of cetane indicate that CN is reduced by a decrease in chain length and branch expansion. Standard CN has been established worldwide and determined by using ASTM D613. Lin and Lin (2007) found that the high CN resulted in more efficient ignition, less occurrence of knocking, and lower NO_x formation. In addition, Knothe (2005) reported that CN of biodiesel relies on the distribution of fatty acids in the feedstock. Longer carbon chain of fatty acids and more saturated of molecules have high CN. Similarly, Chhetri et al. (2008) reported that CN of WCO increased to 61, because WCO has higher amounts of saturated fatty acids, making the increased saturated fatty acids to positively enhance the CN. Finally, the oxidative stability of WCO also increases due to the presence of higher amount of saturated fatty acids.

2.4.3 Density

Diesel engine has a predictable variation in power output depending on the density of the fuel. Density is the relative mass of the material at a specific temperature. As stated by Sandu and Chiru (2007), the importance of fuel has a direct impact on engine performance characteristics. Many fuel properties such as cetane numbers, dynamic viscosities and kinematic viscosities are related to density. Also, the density of fuel affects the efficiency of fuel atomization and combustion characteristics due to the DF injection system mass of fuel according to the volume. Furthermore, the change in fuel density will influence the power output of the engine that causes injected fuel in different mass. Barabás and Todoruț (2011) proposed the utilization of biodiesel-diesel-ethanol blends in CI engines, and concluded that ethanol density is lower than DF, while biodiesel density is higher than DF. As such, the data on density was then required to formulate the correct reactors, storage tank, process piping, distillation units and separation process. Moreover, Muralidharan and Vasudevan (2011) stated that the density of waste cooking oil methyl ester is higher by 6.59% compared to DF, thus making the BSFC of B40 (60% DF and 40% biodiesel) to be getting lower for compression ratio 21, which is 0.259kg/kwh. This is due to the B40 that is composed of higher energy content and decreases in the calorific value for higher concentration blends.

On the other hand, in the production of biodiesel from POME, crude palm tree provides different density as the resulting density undergoes a trans-esterification process in the presence of a catalyst to form esters and glycerol. Therefore, it helps in higher cetane numbers, lower emissions, highest combustion efficiency that satisfies engine performance demands (Leung et al. 2010). In addition, the quality of alcohol added in tri-fuel blends also has an impact on the tri-fuel blends density (Enweremadu and Mbarawa 2009). However, the density of biodiesel is usually higher than DF. The results have been approved by De Almeida et al. (2002) which stated that palm oil has a higher density of 4.6% compared to DF which affects engine performance and emissions improvement.

2.4.4 Kinematic viscosity

Kinematic viscosity is important to measure the flow resistance of the fluid. The kinematic viscosity has an effect on atomization quality, fuel spray penetration, the size of fuel drops, and the combustion of diesel engines. In the same vein, fuel kinematic viscosity has an upper and lower limit, which viscosity must be low enough to flow freely at the lowest operating temperature. On the other hand, low viscosity tends to cause leakage in the fuel system, while high viscosity will cause poor fuel atomization and incomplete combustion, increases the engine deposits, and requires more energy to pump fuel. However, in cold weather, diesel engines get problems if the viscosity increases when the temperature drops. More so, kinematic viscosity of biodiesel also effects the injection and provides excellent lubrication in the diesel engine to avoid fuel pumps from premature wear and tear. Lubricity has the ability of the fuel to reduce the friction between surfaces under load. The ability will reduce the damage caused by friction in fuel pumps and injectors, while the fuel surface tension is a very important parameter in the formation of droplets and combustion fuels. As such, the formation of droplets from liquid fuels become difficult on high surface tension.

In another development, POME has high viscosity which is a major obstacle that causes clogging of fuel lines, filters and injectors. Based on this, some effective methods have been able to reduce the viscosity in biodiesel, which through trans-esterification, mixing with lighter oil and heating (Bari et al. 2002). The research by Ozsezen and Canakci (2011) investigated the determination of diesel engine performance with canola and waste palm oil methyl ester and stated that BSFC of canola increases due to the higher kinematic viscosity, thereby affecting the atomization ratio which causes the slowing down of the air-fuel mixing rates. In order to reduce the kinematic viscosity of POME, the trans-esterification process is required in edible oil converted to biodiesel. In addition, Esteban et al. (2012) reported that the vegetable oil viscosity and density are higher than DF, the viscosity has deep impact on combustion of existing diesel engines and reducing the value of DF by heating. According to Prasad et al. (2000), the heating process is an effective method to utilise vegetable oils as fuel.

2.5 Combustion characteristics

Combustion characteristics are the methods in investigating test fuel, which is related to ignition in the combustion chamber. A good combustion happens when the ignition of the burning material completely burned without it being incombustible, and a good combustion generates power when an appropriate amount of fuel is injected into the fuel chamber. Combustion can be affected by several problems, such as ignition time, cylinder pressure, fuel properties and injection time. In-cylinder pressure, maximum heat release rate, brake power and torque are parts of the combustion characteristics.

2.5.1 In-cylinder pressure

The combustion pressure curve is the internal pressure data in a cylinder combustion chamber that occurs during the combustion process. The ability of the fuel to be well-mixed with air and burns is usually visualized in a cylinder pressure graph, as shown in Figure 2.2. The time interval between the start of ignition (SOI) and the start of combustion (SOC) occurs during ignition air-fuel mixture known as ignition delay (ID). The liquid fuel is injected at high velocity as one or more jets through a small orifice or nozzle in the injector tip. Also, the fuel spray atomizes into small droplets and penetrates to the combustion chamber. Then, the atomization fuel absorbs heat from the surrounding heated compressed air, vaporizes and mixed with high-temperature in high pressure air. As such, when the piston continues moving closer to top dead centre (TDC), the air temperature reaches the fuel ignition temperature. Thus, rapid ignition of some air-fuel mixture occurs after an ignition delay period, and rapid ignition is considered as the start of combustion marked by a sharp cylinder pressure increase as combustion of the air-fuel mixture.

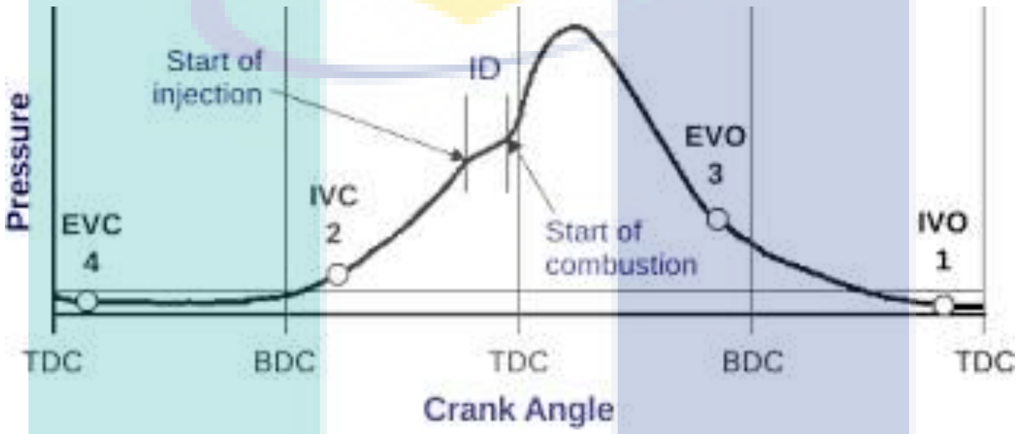


Figure 2.2 Combustion in diesel engines
Sources: Heywood, J.B. (1988)

The theory of pressure data (collected with respect to crank angle) and cylinder geometry, V and pressure data dv/dθ terms are shown in Equation 2.1 and 2.2 below.

$$V = VC + Ar\left[1 - cos\left(\frac{\pi\theta}{180}\right) + \frac{1}{\lambda}\left\{1 - \sqrt{\lambda^2 sin\, 2\frac{\pi\theta}{180}}\right\}\right] \qquad 2.1$$

and

$$\frac{dV}{d\theta} = \left(\frac{\pi\theta}{180}\right)\, X\, r\left[sin\frac{\pi\theta}{180} + \frac{\lambda^2\, sin\, 2\frac{\pi\theta}{180}}{2\, X\sqrt{1 - \lambda^2\ sin\, 2\frac{\pi\theta}{180}}}\right] \qquad 2.2$$

An experimental effect additive on combustion characteristics of diesel engine fuelled with biodiesel was conducted by Kannan et al. (2011), and it was found that the cylinder gas peak pressure increases due to the increase of BMEP. It was further discovered that, at 7 bars, the peak pressure in-cylinder of biodiesel is slightly higher compared to DF. This is because the shorter ignition delay of biodiesel (waste cooking oil) and better combustion resulted into the presence of a fuel borne catalyst (FBC) in waste cooking oil. Nowadays, the start of combustion is getting earlier due to the advancement in fuel injection timing, and small droplets of injected fuel at a high injection pressure as well as high oxygen content of waste cooking oil, thereby leading to a better combustion. Previous researchers by Agarwal et al. (2013), concluded an increase average of 6.45% in maximum cylinder pressure at 9.375 bTDC and the quality of injected fuel was compared to other start of injection (SOI). This was due to richer mixture that was formed inside the chamber, which burns more rapidly in early premixed combustion and fuel burns in late stage. Moreover, Sahoo and Das (2009) have investigated combustion analysis of Polanga, Jatropha and Karanja biodiesel as a fuel in the diesel engine, and it was concluded that Polanga, Jatropha and Karanja biodiesel (PB100), (JB100), and (KB100) that resulted in a maximum peak pressure cylinder were higher by 8.5%, 7.6% and 6.9% compared to DF. The peak pressure occurs close to TDC, causing severe engine knock, thus affecting engine durability.

2.5.2 Heat release rate (HRR)

The heat release rate (HRR) is a critical parameter for an evaluation of mixing controlled in estimates of the rate of air-fuel mixture. It is the composition within the combustible limit that is produced in diesel spray under normal engine condition. The HRR profiles show trends with crank angle (CA). Longer ignition delay allows more fuels to mix within combustible limits during the suspension, thus peak premixed HRR will be increased. Nevertheless, the phase-mixing controlled HRR magnitude is essentially the same due to the spray mixing process that is affected by changes in air temperature. Figure 2.3 shows the combustion in HRR diesel engine, which consists of four phases:

a) Ignition delay period.

b) Premixed combustion phase.

c) Mixing-controlled combustion phase.

d) Late combustion phase.

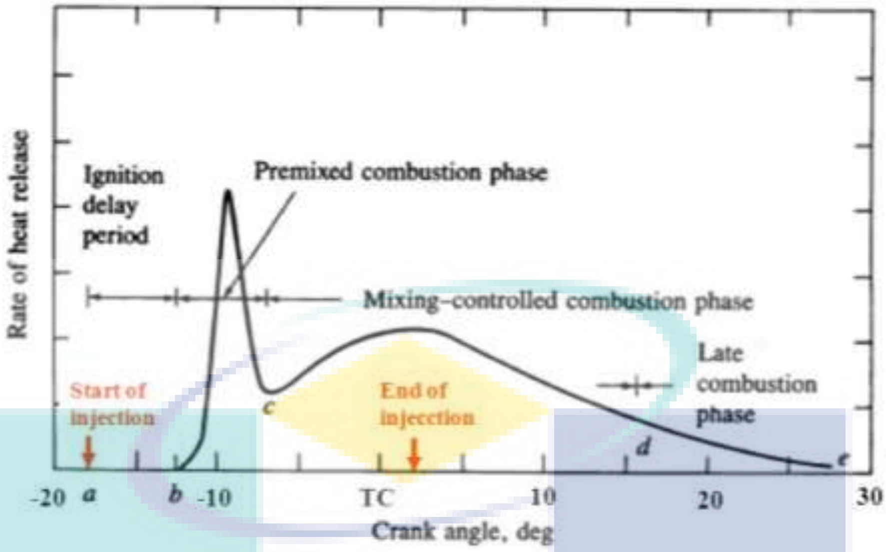


Figure 2.3 Four stages of combustion in CI engines
Sources: Heywood (1988)

The ignition delay (ID) of both physical and chemical processes must take place before significant fragments chemical energy of the injected fuel is released. The physical process is the atomization of liquid fuel jets, vaporization of the fuel droplets, and mixing of the fuel vapour with air. While for chemical process, it is a pre-combustion reactions of air-fuel and a residual gas mixture which leads to auto ignition. Chemical delay is more effective for the duration of ID period that occur in the first phases. The second phase is a premix combustion phase, which is combustion of fuel that has mixed with air within flammable limit during ID. The highest HRR occurs rapidly in several degrees CA within the range of 0.2 to 0.3MPa/°CA. The highest amount of fuel accumulated in the combustion chamber during ID, results to high HRR in a rapid pressure rise, and causes the diesel knock. In addition, for fuel that has low cetane numbers, with long IDs, or late ignition occurrence in the expansion stroke, this will cause incomplete combustion, reduces power output and poor fuel conversion efficiency respectively. Once air-fuel mixture during ID has consolidated, the HRR is controlled by the rate at which mixture is available for combust. The rate of combustion is mainly controlled by the mixing process of fuel vapour and air. Also, HRR has been affected by fuel atomization, vaporization and pre-flame chemical reaction. Generally, it is desirable to have a combustion process near TDC for low emission and high efficiency performance occurrence at mixing controlled combustion phases. The last phase is the late combustion phase where HRR continues at a lower rate into the expansion stroke, due to a small fraction of the fuel that may not burnt again. Therefore, a fraction of the energy is present in soot and fuel-rich combustion products and released.

HRR was obtained from the cylinder pressure data and crank angle data. It was derived from the first law of thermodynamics, an open quasi static system, as shown in Equation 2.3 below.

$$\frac{dQ}{d\theta} = \left[\left(\frac{\kappa}{\kappa - 1}\right) P \frac{dV}{d\theta}\right] + \left[\frac{1}{\kappa - 1} V \frac{dP}{d\theta}\right] \qquad 2.3$$

where $\frac{dQ}{d\theta}$ = Heat release rate

The rise of peak pressure and maximum rate pressures was related to a large amount of fuel burnt during those phase. Sathiyamoorthi and Sankaranarayanan (2017), investigated the effect of ethanol with neat lemongrass oil-diesel fuel blends on combustion and emission and stated that the maximum HRR additive fuel ethanol and lemongrass is higher by 51.54% and 49.66% with ethanol concentration of 5% and 2.5% compared to DF. The study also discovered that HRR significantly increased with added addition ethanol, containing oxygen in the fuel blends increased. This is due to the preparation of a larger portion of fuel for rapid combustion during longer ID period. On the contrary, Qi et al. (2009) reviewed the combustion and performance of diesel engine with soybean crude oil, and biodiesel was observed to experience identical combustion stage with DF. It was discovered that at low engine load, HRR for DF was slightly lower than biodiesel, while at high engine load, HRR for DF was higher. The maximum HRR, which is the crank angle (CA) takes precedence for biodiesel. This is because the SOC after TDC for biodiesel and DF at low engine load as well as the delay of combustion starts for DF was compared to biodiesel. It was discovered that at high engine loads, HRR for DF was higher due to longer ID during more fuel that was accumulation in the combustion chamber to release higher heat occurrence during premixed combustion phase.

2.6 Engine performances

The performance of diesel engine is basically related to the engine design, running parameters and fuel properties. These are important for the optimization of the engine's performance (İçıngür and Altiparmak 2003). The BSFC and BTE measures engine fuel consumption as well as engine performance efficiency. In fact, BSFC and BTE are inversely related, which means the lower the BSFC, the higher BTE will be improving the performances in diesel engine (Çelik and Arcaklioğlu 2005). On the other hand, the presence of biodiesel and alcohols may lead and gain better performance for diesel engines.

2.6.1 Brake thermal efficiency (BTE)

The BTE of an engine is important because it determines how efficiently the fuel is being used in the engine. This is to measure the ratio of work done by the engine to the heat supplied to the engine, which is specified as heat engine efficiency. This parameter is a better evaluation than fuel consumption for performance of different fuels, besides heating fuels. Since BTE is synonyms with the fuel heating value, thus it relies heavily on how the way energy is converted.

In Equation 2.5 brake thermal efficiency was expressed in formula. The fuel power was calculated using Equation 2.4.

$$\textit{Fuel power} = \textit{Mass of fuel x calorific value} \qquad 2.4$$

$$BTE = \left[\frac{Engine\ power}{Fuel\ power}\right] \qquad 2.5$$

Recent studies by Venkata Subbaiah and Raja Gopal (2011), found that the performance and exhaust emission characteristics of a DI diesel engine when fuelled with rice bran oil (RBD) biodiesel with 2.5%, 5% and 7.5% ethanol, BTE of 2.5% ethanol was higher by 6.98% and 3.93% compared to DF and RBD respectively. The reason is due to the reduction of viscosity and density of fuel by the addition of smaller amounts of ethanol. However, short-chain alcohols, like ethanol shows that the ethanol-diesel blend leads to BTE decrease by 17% due to the lower of LHV than DF (Sayin and Canakci

2009). Also, palm oil-based biodiesel fuel contains more oxygen content compared to diesel. The bonding oxygen helps fuels to burn efficiently in the combustion chamber, thus releasing more heat. Therefore, combustion of palm oil is better compared to diesel (Vedaraman et al. 2011). Accordingly, the analysis of blended fuel properties of palm biodiesel-butanol-diesel blend fuel B10, B20 and B30 by Ali et al. (2016), found that BTE test fuel increased by 21.8%, 21.6% and 21.9% of B10, B20 and B30 compared with mineral diesel. The difference is due to the high oxygen content of the blended fuel compared to mineral diesel, thus enhancing the fuel combustion process and addition of palm oil obtains by the lubricity. The results correspond to Buyukkaya (2010), in effect of rapeseed oil on a DI performance, emission and combustion characteristics. The authors were concluded that BTE of B5, B20, B70 and B100 of rapeseed oil increased by 0.94%, 0.47%, 0.47% and 0.23% compared to DF at engine speed 2000 rpm. The improvement of BTE is done by increasing the concentration biodiesel in fuel blends due to the possibility of lubrication provided by biodiesel. In addition, Karabektas and Hosoz (2009), evaluated the performance and emission characteristics of a diesel engine using isobutanol-diesel fuel blends. In the test operation, BTE was relatively at high values for a blend up to 10%, which was encouraging to promote combustion due to the oxygen content of blends. Furthermore, the use of ISB10 blends, slightly improves BTE at high engine speed due to the compensation of the lower cetane number through high cylinder temperature. Atmanli (2016), studied the comparative of diesel-waste oil biodiesel and propanol, as well as n-butanol or 1-pentanol blends in diesel engines. The values of BTE of D40B40nB20 and D40B40Pn20 were found to increase by 5.58% and 4.49% compared with D50B50. This is because the presence of more oxygen in the higher atomic structure of alcohol may create better combustion and reduction in heat losses due to lower boiling point of higher alcohol compared to DF (Li et al. 2015). Most of the studies conducted on different types of alcohol, and long-chain alcohol was investigated by Raju et al. (2016), which examined the engine performance of DI diesel engine fuelled with 1-hexanol as a fuel additive in mahua seed oil biodiesel blends. The BTE increased by 2.04%, 3.68%, and 5.33% for M30, M30D69.5H0.5 and M30D69H1 compared to DF. Among the three-test fuel, the maximum BTE was obtained for M30D69H1 due to addition of ignition improver which effects to decrease viscosity and due to increased concentration of alcohol. The addition of alcohol leading to oxygen content presence to the biodiesel-diesel blends, with extra oxygen to gain and become better combustion inside the combustion chamber.

2.6.2 Brake specific fuel consumption (BSFC)

The increase and fluctuation of process DF and gasoline as well as shortage of petroleum are one of the reasons for generating alternative fuels. However, the trait of alternative fuel at least can decrease the fuel consumption in working engine. The BSFC is a measurable combustion efficiency to measure how efficiently the amount of fuel has been converted to a specific amount of power. An improved combustion has allowed the same amount of fuel to generate an increase in power output that improved combustion efficiency, thus resulted reduced the BSFC.

The BSFC was calculated using Equation 2.6.

$$BSFC\ \left(\frac{g}{kW.h}\right) = \left[\frac{Mass\ flow\ rate,}{Engine\ power, kW}\right] = \frac{\dot{m}}{P_e} \qquad 2.6$$

where BSFC is specific fuel consumption, $\dot{m}$ is the amount of fuel consumed, P_e is the engine power.

Based on the research by Jaichandar and Annamalai (2012), the influences of re-entrant combustion chamber of 20% pongamia oil methyl ester biodiesel was compared to DF on performance in a DI diesel engine. These researchers presented that overall, BSFC decreases with the increases in brake power. However, at a brake power of 5.024kW, BSFC for shallow depth re-entrant (SRCC) 0.271 kg/kW-hr and hemispherical (HCC) 0.288 kg/kW-hr, it was slightly higher than toroidal re-entrant (TRCC) 0.252 kg/kW-hr when fuelled with 20% pongamia oil methyl ester biodiesel. This may be attributed to poor air-fuel mixing, which leads to poor combustion, thus resulted to higher BSFC. In contrary, Imdadul et al. (2016) stated that BSFC improved in higher alcohol-biodiesel-diesel of a light-duty diesel engine. The maximum BSFC average reduction is 10.87% for 20% crude oil and 20% pentanol as well as 60% DF (C20P20) compared to CI 20. This is because biodiesel crude oil has higher viscosity and density compared to other test fuels, thus resulting in adhesion fuel into the cylinder wall due to the high spray penetration that might occur for an appropriate atomization. Moreover, CI 20 also attributed to the improved ignition quality caused by the larger amount of oxygen. Conversely, the addition of pentanol blended fuel as well provides retarded injection timing because of low BSFC. The BSFC improvements were also agreed by Zhang and

Balasubramanian (2014), who carried out study on the experiment and found that alcohol leads to a 1% reduction in BSFC that improves combustion characteristics in diesel engines. Nevertheless, the reduction of BSFC in 20% POME concentration was due to better air-fuel mixing that leads to better atomization and vaporization of the fuel, and resulted to better combustion (Jaichandar et al. 2012). In addition, Campos-Fernández et al. (2012) found BSFC to be getting lower with the addition of butanol and pentanol. This is due to 15% and 20% of butanol, which involves higher oxygen content, lower viscosity and butanol molecular weight leading to more complete combustion. Overall, the literature review carried out in the present study, found that long-chain alcohols, such as pentanol and hexanol have the advantage of minimizing BSFC compared to short-chain alcohol, ethanol and methanol.

2.6.3 Brake power and brake torque

On this topic, there are a few researchers that have interpreted the effect of additives with biodiesel on engine power and torque (Dhar et al. 2012, Özener et al. 2014). Some of them reported that engine power is reduced when using biodiesel fuel due to the lower heating value (Karabektas 2009, Radu et al. 2009). Based on the literature by Ozsezen et al. (2009), the performance and combustion characteristics of a DI diesel engine is fuelled with waste palm oil (WPOME) and canola oil methyl ester (COME). It was stated that brake power was reduced by 2.57% and 2.71% for WPOME and COME respectively compared to DF. This result showed that the chemical energy content of all fuel test turns into mechanical work in a similar manner. Another similarity between WPOME and COME occurs in the brake power. However, engine power increases with the increase in biodiesel percentage in fuel blends due to high oxygen content, proper injection timing and higher cetane number (Song and Zhang 2008). Significantly, the properties of biodiesel are effected on brake power, such as viscosity, heating values and lubricity (Xue et al. 2011). Additionally, there are few researchers that have reported the effect of different additives and show different results in engine brake power. For example, Fangsuwannarak and Triratanasirichai (2013) studied the effects of metalloid compound and bio-solution additives in biodiesel engine performance and exhaust emissions, and they found that nano-titanium as based additive is a more effective improve engine power compared to DF as well as 5% concentration of palm biodiesel (B5) by 7.78% and 1.36% respectively. Also, the usage of additives in fuel blends, which increases brake power was observed and the results from the conversion efficiency increases through the complete combustion process.

Furthermore, Mofijur et al. (2012) also carried out an experimental study of additive added palm biodiesel in a compression ignition engine with additive 4-nonyl phenoxy acetic acid (NPAA), and found B35 fuel with 1% NPAA having a brake power increase by 6.12% compared to DF, due to lower viscosity and quality combustion of additives. Biodiesel fuel has no significant effect on engine torque and the power output, but TiO_2 additive improves engine performance. The existence of oxygen in the molecular structure 1-butanol and n–pentanol offsets the reduced low heating value, indicating better combustion that leads the power and torque to meet net diesel fuel. In addition, Bilgin et al. (2002) used a diesel-ethanol blends on diesel engine performance, and reported that the increases blend ratio, would increase the average brake torque by 1.5% for compression ratio of 21. In spite of the heating value of ethanol that is lower than DF, it is yet leading to increase in power and torque. Raheman and Phadatare (2004), carried out the variation of torque in diesel engine performance of karanja methyl ester and diesel fuel blends, and found that brake torque increased by an average of 0.1-13% for B20 and B40, due to complete combustion of test fuels. Contrarily, B60 and B100 reduced by 4-23% compared to DF, due to a decrease in fuel calorific value with an increase in the biodiesel percentage of blends.

The brake power and torque can be calculated using Equation 2.7 and Equation 2.8 below.

$$Brake\ power\ (W) = \left[\frac{2\pi NT}{60}\right] \tag{2.7}$$

$$Torque\ (Nm) = [Wr] \tag{2.8}$$

2.7 Exhaust emissions

Although diesel engines provide better fuel efficiency than gasoline engines. However, it has higher exhaust emissions that have a damaging effect on the environment and humans. This is because exhaust emissions from diesel engines are produced from combustion of heterogeneous air-fuel mixture. In this study, the exhaust emission components of the diesel engine discussed are CO, CO_2 and NO_x.

2.7.1 Carbon Monoxide emission

The CO emission is some poisonous gas traits that is colourless, odourless and tasteless, which are released by partial oxidation of hydrocarbon fuels during combustion. CO is one of the intermediate compounds formed by incomplete combustion of fuel in the engine due to the local area with insufficient air supply. The increase of biodiesel content in the fuel blends, will also increase oxygen content, thus making CO emission to reduce.

Conversely, CO emissions are also affected by feedstock of biodiesel by the enhancement of long-chain molecular structure that result into reduction of CO emissions. This trend was reported by Wu et al. (2009), who found five biodiesel methyl ester, namely; (i) cottonseed methyl ester (CME), (ii) soybean methyl ester (SME) , (iii) rapeseed methyl ester (RME), (iv) palm oil methyl ester (PME), and (v) waste cooking oil methyl ester (WME) that reduce CO emission by 4-16% on average. The large effect of cetane number and oxygen content may be helpful in reducing CO, and the hypothesis can be made when cetane number increases, and CO decreases consistently for both biodiesel and DF. In addition, CO emissions are reduced with an increase in cetane number of biodiesels, engine load and engine speed. The reduction of CO emissions that is reduced by 64.28% in the impact of Mn and Ni based additive in high biodiesel on fuel properties, fuel consumption and emission at full load conditions by Keskin et al. (2007). However, positive impact was found by Mahalingam et al. (2018), in emission and performance analysis on the effect of EGR in alcohol-biodiesel aspired research diesel engine with results of CO emissions for pentanol at 10% and 20% blended with DF which was reduced by 3.1% and 4.2% respectively compared to DF. The reduction of CO emissions was due to improved combustion rates in the hydroxyl group and pentanol which causes oxygen atoms to bind during combustion and lead to lower soot formation by slowing down soot formation as well as increase oxygen availability. The research done by Gopal et al. (2014) showed that the reduction of CO emission in waste cooking methyl ester (WCME) blends lower than DF. The reduction of CO emissions was reduced by 59%, 38%, 35% and 31% for ratio concentration waste cooking methyl ester 20%, 40% 80% and 100% compared to DF operation. The result of CO emission was due to the oxygen content in biodiesel, which allows more carbon molecules to oxidize when compared with DF.

2.7.2 Carbon Dioxide emission

The engine operates with biodiesel fuel effuse CO_2 emission, which is the elementary source of greenhouse gas effect. However, as trees and plants are the resources of biofuels and because CO_2 is very important for growth, the use of biofuels does not add CO_2 to the atmosphere, it simply recycles what's already there. CO_2 is a typical combustion product. Most of the available literature found lower CO_2 with the addition of alcohol due to the increase in hydrogen (H) and oxygen (O_2) molecule in the fuel blends.

The examples of lower CO_2 are reported by Gomez et al. (2000), who showed a reduction of CO_2 to be approximately by 7.5% for waste cooking oil methyl ester at 4800 rpm engine speed compared to DF. When a sufficient of oxygen is available, hydroxyl radicals OH are one of the principal oxidizing agents that convert CO into CO_2. Imdadul et al. (2016) investigated the approach to improve the performance, emissions and combustion in light-duty diesel engine fuelled by DF and biodiesel by adding pentanol (10%, 15% and 20% by volume). They pointed out that CO_2 emissions slightly decreased in an average 2.5% of C10P10, C15P15 and C20P20 at a maximum engine speed of 2400 rpm compared to pure biodiesel. When a test fuel chemical structure is considered, the pentanol has a lower carbon atom per unit volume. Conversely, the reduction of CO_2 emissions, was due to the increase in oxygen and hydrogen molecules in fuel structure. Biodiesel and oxygenated biofuels require less oxygen molecules than DF due to the higher oxygen molecules in the chemical structure. The same result was acquired by Suhaimi et al. (2018), who analysed combustion characteristics, engine performances and emissions of hexanol 5%, 10% and 20% concentration by volume in diesel engine. The results showed that CO_2 emissions were reduced by 25.3% for HE10 due to lower viscosity and calorific value than DF. In addition, lower operating temperatures occur in diesel engines, resulting in a high latent heat vaporization of 2-ethyl1-hexanol. This statement is supported by Ileri et al. (2016), who stated that the increase of oxygen and hydrogen molecules in fuel structures results in a reduction of CO_2 emissions. The most effective way to reduce CO_2 emissions is to reduce DF consumption by blending or replace with biodiesel or bio fuels.

2.7.3 Nitrogen Oxide emission

The most dreadful emission from compression ignition engine is NO_x. The nitrogen oxide in exhaust emission consist of nitric oxide (NO) and nitrogen dioxide (NO_2). The formation of NO_x emissions occurs during both premixed and diffusion phases. This formation of NO_x depends highly on the temperature inside the cylinder, the concentration of oxygen, residence time for the reaction and equivalence ratio. There are several reasons reported to increase NO_x emissions, such as increase oxygen, lower cetane number, and additive fuel.

In 2016, Venkatesan and Kadiresh (2016) studied the effect of jatropha biodiesel fuel blended with cerium oxide on engine performance and emission of a compression ignition diesel engine at different loads. The authors found that the use of additive cerium oxide reduces NO_x emissions by 23.5% compared to DF. This is because the combustion of hydrogen produces a more complete combustion, thereby making NO_x emission of test fuel lower than DF. The latent heat of evaporation water and its heat capacity also reduces the temperature in the combustion chamber, thus retarding NO_x formation. According to Balaji and Cheralathan (2014) who studied the effects of antioxidant additive (L-ascorbic) fuelled with cottonseed methyl ester of a direct injection, they found that L-ascorbic acid additive with cottonseed methyl ester, NO_x emission was reduced by 9.31% at full-load condition compared with pure biodiesel. However, the reduction of NO_x emission was due to reducing the formation of free radicals by antioxidants. Moreover, Sharon et al. (2013) revealed that NO_x emission decrease when DF fuelled with butanol 5%, 10% and 15% by volume that is reduced to 1.74%, 2.53% and 5.15% compared to DF. Test fuels containing butanol showed a reduction of NO_x emission despite its higher oxygen content, which was due to the effect of lowering the butanol temperature caused by high latent heat of evaporation. The reduction of NO_x is important to be an objective to achieve the most harmful emission caused by diesel engines.

However, biodiesel can be suggested as the main reason for the formation of increased NO_x emission. Firstly, it is faster fire's rate and advanced SOCs. Secondly, it has a low radiation heat transfer and low adiabatic flame temperature. Muralidharan and Vasudevan (2011) found that the NO_x emission for DF and test fuel increased with an increase in compression ratio. The NO_x formation of butanol 40% concentration increased by 3.06% compared to DF at compression ratio 21. The higher NO_x emission B40 was due to higher peak pressure.

2.8 Optimization by Response Surface Methodology (RSM)

In complex variables process, choosing the optimum matching variables for the product would be time consuming and must be captured conventionally (one by one). Response Surface Methodology (RSM) is a widely used technique for solving many industrial problems (Najafi et al. 2015). RSM is one of the most practical and economical solution for evaluating the single and combined factors of experiment variables that lead to output response (Asghar et al. 2014). Therefore, it is essential to have an analysis and capability to find the optimum blend ratio of product to know the selective product that meets the RSM demand that is statistically and mathematically able to be used for analysing, modelling, optimizing and determining interactions between variables and responses. RSM can be well applied when responses or a set of interest responses are influenced by several variables. The aim of RSM analysis is to build a model, evaluate the effect of variables and establish optimum performance conditions by using experimental design and regression analysis. Moreover, RSM is used simultaneously to optimize and find the levels optimum blend ratio of variable to attain the best system performance. Systems, processes or products need some improvement in performance, and optimizing significantly is the best method to get maximum benefits by using RSM. Currently, RSM is among the most multivariate techniques used to fuel to find the best selective analytically optimum blend ratio.

The most extensive application of RSM are in those situations where several input variables potentially influence some performance measure or the quality characteristics of the process RSM has been applied for optimization of several chemical and physical process. Initially, RSM was developed to model experimental responses and then migrated into the modelling of numerical experiments.

Previous study Yusri et al. (2017) used RSM optimization method to indicate the optimum blending ratio for gasoline-butanol blends under different engine speeds. The author showed the optimum mixing ratio of gasoline-butanol regarding the performance and emission of spark ignition engine it was GBu15 (85% gasoline + 15% butanol) at 3205rpm. (Pandian et al. 2011) was investigated the effect pongamia biodiesel-diesel blend using RSM. The authors stated desirability approach of the RSM was found to be the simplest and efficient optimization technique. A high desirability of 0.98 was obtained at optimum injection system 225 bar of injection pressure, 21^{o} BTCD of injection timing. In addition, BSEC, BTE, CO, and NO_x emission were found to be 14.12MJ/kWh, 25.39%, 0.48% and 215 ppm respectively.

CHAPTER 3

METHODOLOGY

3.1 Introduction

In this chapter, the experimental method for this research will be discussed. This will include the experimental method as well as the flow of work been conducted in this research. The process and streamline of research are being utilized to carry out all the steps from beginning until the end of this study. This experiment is carefully designed to analyse the effect of long-chain alcohol-biodiesel-diesel tri-fuel blends on combustion characteristics, engine performances and exhaust emissions of a diesel engine. All experimental procedures were conducted in order to achieve all research objectives, as illustrated in Figure 3.1.

The flowchart was started with the identifying problems, objectives and scope of research. Then proceed to the fuel blending process, which is the combination three type of substance DF, POME and 5%, 10% and 15% of PE and HE, to formed tri-fuel blends. the tri-fuel blends were named as D85-B10-PE5, D80-B10-PE10, D75-B10-PE15, D85-B10-HE5, D80-B10-HE10 and D75-B10-HE15. The fuel blending was blended using ultrasonic emulsifier with specific parameter was set at 70% amplitude and 0.5 cycle with duration 2 minutes. The tri-fuel blends were tested before and after running the fuel into diesel engine. Before running fuel into diesel engine, coming to the first objective, visual separation observation analysis or stability test. The observation stability test was to find either the tri-fuel blends shows has separation or no separation. If there is no any phase separation the tri-fuel blends can be continue to running the fuel in diesel engine. However, if the tri-fuel blends have phase separation, the tri-fuel might be damaging the engine if continuing running the fuel in diesel engine. Therefore, for better combustion and engine performance efficiency, the tri-fuel need to redo with other ratio blending or others substance of fuel blends. Next, measure the thermo-physical properties of fuel blends. The thermo-physical properties are to identify either the properties of fuel blends on par with DF. The thermo-physical properties comprising of cetane number, calorific value, density, dynamic viscosity and kinematic viscosity.

Second objective is running experiment in diesel engine YANMAR TF120M, single cylinder, and analyse the effect of combustion characteristics, engine performance and exhaust emission of blended fuel varying engine load and constant engine speed. The combustion characteristics consists of in-cylinder pressure and heat release rate. While for engine performance comprising brake specific fuel consumption, brake thermal efficiency, brake power and brake torque. Lastly, carbon monoxide, carbon dioxide and nitrogen oxide for exhaust emissions. The tri-fuel blends various engine load and constant engine speed.

Lastly, is third objective that optimization of blend ratio is observed. The optimization used Response Surface Methodology (RSM) software. From the analysis it will get the selective best blend ratio among the tri-fuel blends. Analyse and concluded all the data and thesis writing. Final presentation and ended.

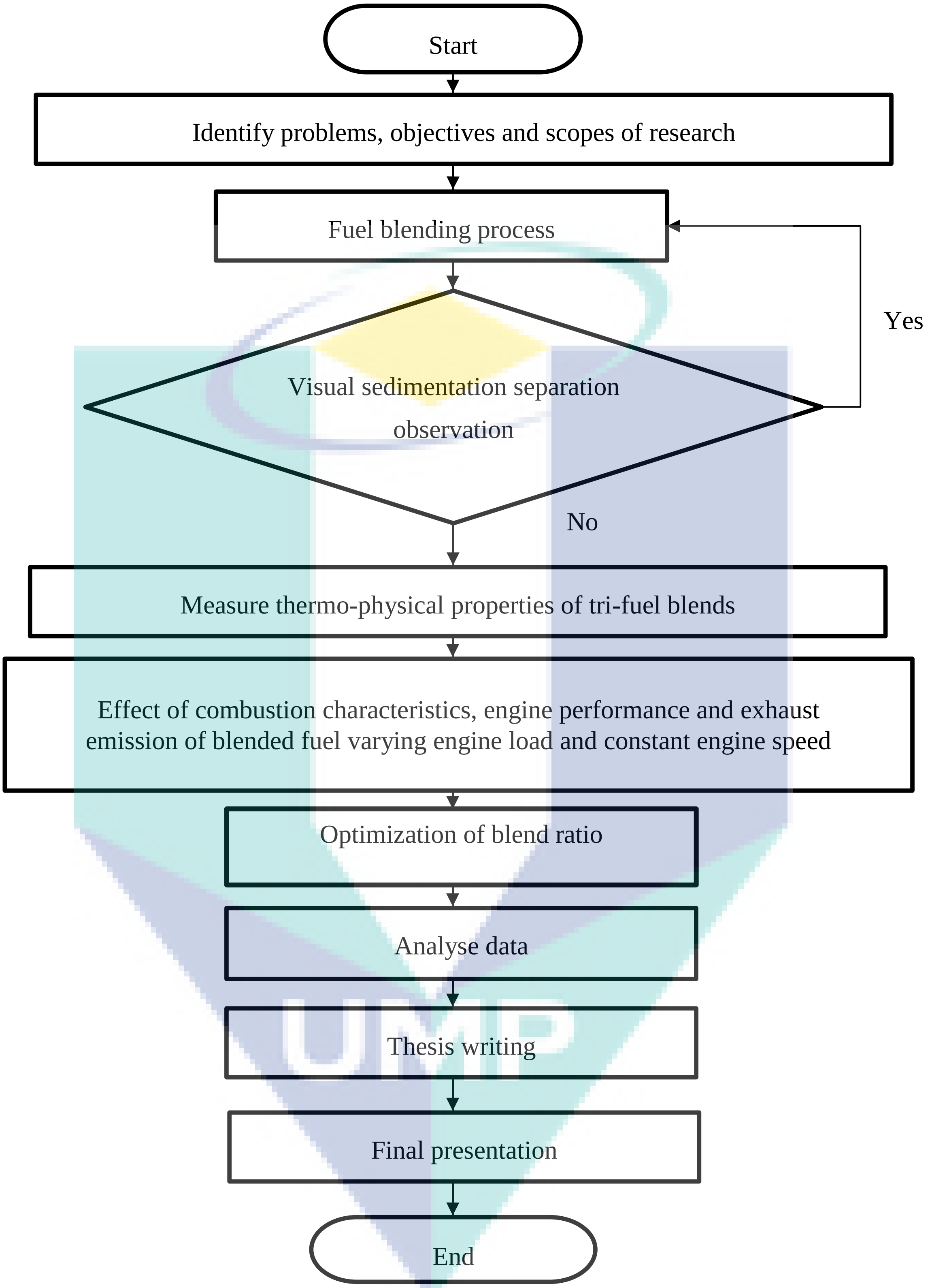


Figure 3.1 Flowchart of research

3.2 Materials and variables

In this research, the new formulation of long-chain alcohol-biodiesel-diesel tri-fuel blends consist of two types of long-chain alcohol. The long-chain alcohol selected are 1-pentanol (PE) and 2-ethyl-1-hexanol (HE) brand ACROS as additive fuel. The molecular formula of PE ($C_5H_{11}OH$) and HE ($C_8H_{17}OH$). Meanwhile, the biodiesel used in this research was palm oil methyl ester (POME) which supplied from FGV Biotechnology Sdn. Bhd. DF pure diesel JIS#2 (Japanese Industrial Standard). The concentration ratio by volume of long-chain alcohol were 5%, 10%, and 15% for both PE and HE, constant volume concentration of POME with 10%, and the rest 85%, 80% and 75% volume concentration for DF that named D85-B10-PE5, D80-B10-PE10, D75-B10-PE15 for 1-pentanol-biodiesel-diesel tri-fuel blends and D85-B10-HE5, D80-B10-HE10 and D75-B10-HE15 for 2-ethyl 1-hexanol-biodiesel-diesel fuel blends, as tabulated in Table 3.1.

The advantages of long-chain alcohol are its high density, calorific value and cetane numbers compared to short-chain alcohol that is hypothetically, in which when blended with diesel or biodiesel can lead to better combustion. Moreover, PE and HE are easy to purchase and safe to use. On the other hand, the POME variety of ester-based oxygenated fuels are from renewable biological sources, due to the POME that is derived from plant oil under the trans-esterification process. Therefore, POME used in this study was 100% crude biodiesel, without addition of any additive. Furthermore, the addition of POME as biodiesel shall increase the oxygen content which could promotes the combustion. Furthermore, because POME has no sulphur content, significant reduction in PM emissions is expected from the exhaust emission measurement. Lastly, the new formulation of long-chain alcohol-biodiesel-diesel tri-fuel blends can be a substitute and minimize the usage of DF and fossil fuel sources.

In this experiment, the parameters of YANMAR TF120M single cylinder, as well as direct injection diesel engine was fully utilized throughout the experiments. The experiment was conducted in 5 engine loads, which were 0 Nm, 7 Nm, 14 Nm, 21 Nm, and 28 Nm corresponding to engine loads of 0%, 25%, 50%, 75% and 100%. All the engine test measurement was conducted 3 times to ensure the stability of the results and reduce the measurement error. The overall results were compared to DF or B100 as the references.

Table 3.1 Blending ratio

Test fuel	Types of solution
DF	100% diesel fuel (DF)
B100	100% palm oil methyl ester (POME)
D85-B10-PE5	85% DF + 10% POME + 5% PE
D80-B10-PE10	80% DF + 10% POME + 10% PE
D75-B10-PE15	75% DF + 10% POME + 15% PE
D85-B10-HE5	85% DF + 10% POME + 5% HE
D80-B10-HE10	80% DF + 10% POME + 10% HE
D75-B10-HE15	75% DF + 10% POME + 15% HE

3.3 Preparation of long-chain alcohol-biodiesel-diesel tri-fuel blends

This preparation was obtained, the long-chain alcohol blended with constant 10% POME as biodiesel and DF. The blending process was done using the Hielscher UP400S ultrasonic processor. The ultrasonic emulsifier blending process to ensure the solution (long-chain alcohols, POME and DF) was completely dissolved to form a stable long-chain alcohol-biodiesel-diesel tri-fuel blends. However, there were no additives was added in order to stabilize and avoid phase separation. Table 3.2 shows the blending process parameter as was allocated. According to the specified parameter, mixing process was within 2 minutes. The critical factor during the blend process was to ensure the mixing time was controlled not to exceed 2 minutes in order to prevent damaging the chemical properties and fuel elements (Abdullah et al. 2018). Other than that, the temperature of fuel blends was kept between 30°C to 32°C to maintain the chemical properties and prevent destruction of tri-fuel blends elements. All apparatus and equipment used for blending and storing fuel blends were washed and wiped with acetone liquid. Acetone is a solvent that is commonly used to clean a tool which characterize colourless, volatile and flammable organic solvent. The precaution was made to avoid impurity in mixed fuel.

Table 3.2 Parameter blending process

Variable	Parameter
Duration	2 minutes
Amplitude	70%
Cycle	0.5

The tri-fuel blends were prepared for stability observation test, thermo-physical tests and engine performance tests. The blending procedures are performed as below:

a) All the substance 5% of 1-pentanol, 10% of POME and 85% of DF were mixed into 500ml beaker as shown in Figure 3.2.

b) The beaker was placed on a plate in an ultrasonic processor, and a soft cloth placed between the beaker and ultrasonic processor plate to avoid any vibration that could break the beaker.

c) The beaker height was positioned for more than half of the ultrasonic processor horn as shown in Figure 3.3.

d) The ultrasonic processor was set at 70% amplitude and 0.5 cycle. The lid was closed and the stirring process was set for 2 minutes.

e) After 2 minutes, the fuel was ready and stored for stability observation test (test tube) and thermo-physical test (bottle) as shown in Figure 3.4. Test tubes and bottles were labelled as D85-B10-PE5.

f) Step (a) to (d) were repeated to obtain 4 litres of fuel for engine performance tests.

g) Step (a) to (e) were repeated for D80-B10-PE10, D75-B10-PE15, and 2-ethyl-1-hexanol, D85-B10-HE5, D80-B10-HE10 and D75-B10-HE15 referred previous blending ratio in Table 3.1.

After done blending process, for stability observation test (test tube) placed in light box studio photography box kit to capture either the solution of tri-fuel having a separation phase or not. The light box has LED light strips emit even lighting coverage. The tri-fuel was observed by time to time, 1 minute, 1 hours, 1 day and even a month after blending process. Then capture the changes for every time lapse.

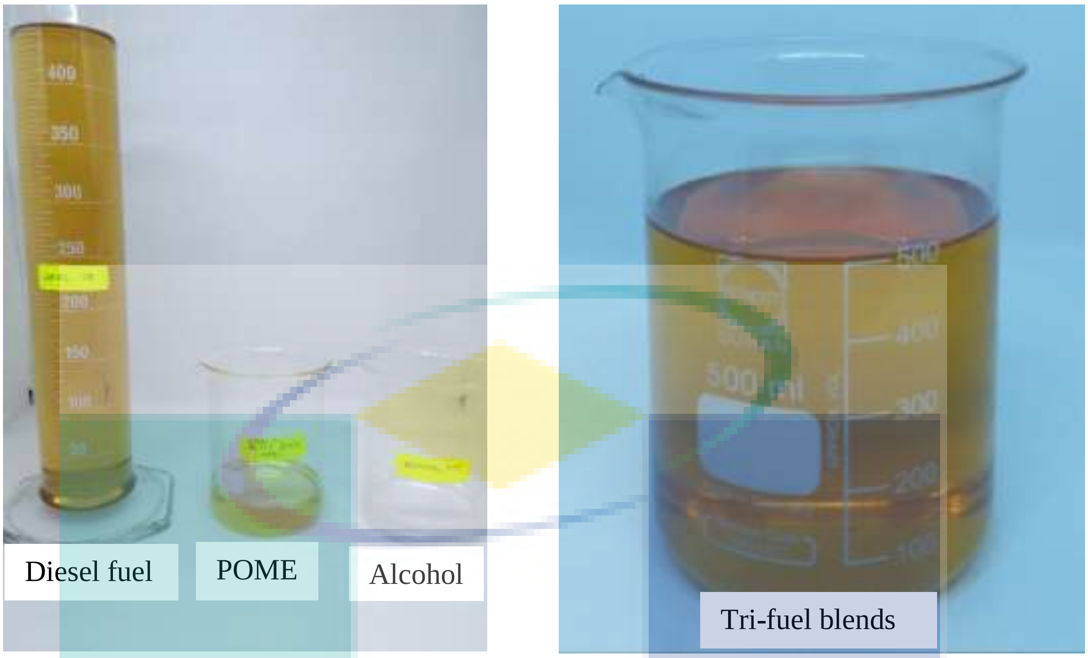


Figure 3.2 Preparation for blending test fuel

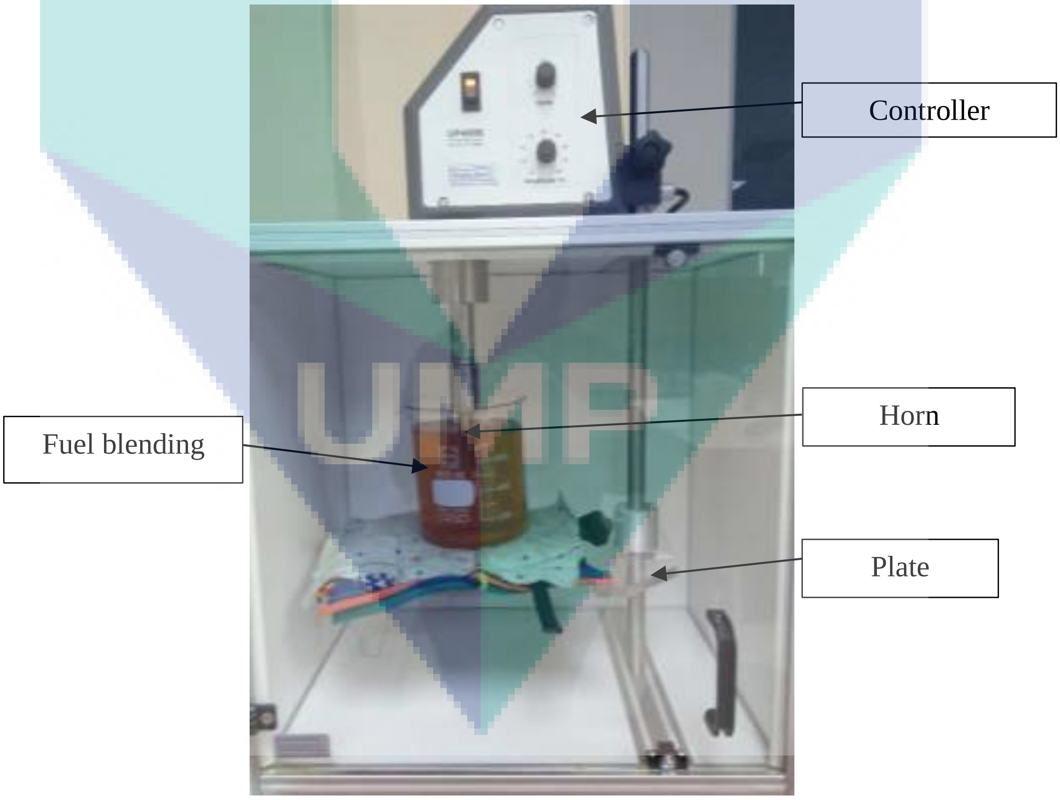


Figure 3.3 Hielscher UP400S ultrasonic processor

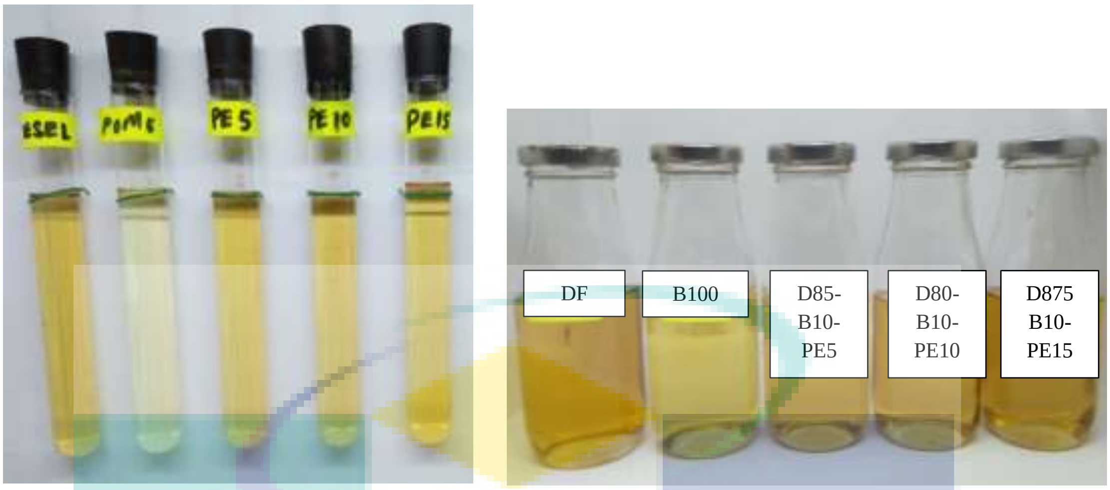


Figure 3.4 Fuel blending for stability test and thermo-physical test

3.4 Thermo-physical properties test

The thermo-physical properties of the long-chain alcohol-biodiesel-diesel tri-fuel blends were characterised strictly in accordance with ASTM standards. The properties measured were the calorific values, cetane numbers, density, dynamic viscosity and kinematic viscosity the equipment used for the thermo-physical properties, and the ASTM type are shown in Table 3.3. Details procedures conducted will be explained further in the following section.

Table 3.3 Properties tested and equipment type

Thermo-physical properties	**ASTM**	**Equipment**
Calorific Value	ASTM D4809	IKA C 3000 isoperibol calorimeter
Density, dynamic viscosity and kinematics viscosity	ASTM D4052	Viscometer, SVM 3001

3.4.1 Calorific value

The IKA C 3000 isoperibol calorimeter system was used to determine the calorific value of solid and liquid substance as shown in Figure 3.5. The purpose of finding calorific value is to look for heat capacity or energy content of a fuel blends. The procedures for calorific values were strictly conducted by the following steps according to the standard ASTM D4809:

a) A sample fuel was added on the crucible (not exceeding 1 gram), then recorded the value.

b) Crucible was placed to the standard electrode.

c) Cotton thread was attached to the centre of the ignition wire using a loop.

d) Put the decomposition vessel on the lid and screwed tightly as shown in Figure 3.6.

e) The IKA C 3000 isoperibol calorimeter was switched on and the cover opened automatically.

f) Touch screen display was active and was operated using the stylus.

g) The decomposition vessel to the IKA C 3000 isoperibol calorimeter was hanged.

h) Key in the weight and name of sample fuel that has been recorded in Step a) to the calorimeter operation.

i) Click ‘Start’ on the screen display and the cover closed automatically.

j) The operation was started and wait for a sample fuel undergoes the combustion about 12 minutes.

k) The ‘beep’ sound came from the calorimeter operation, meaning completely burned.

l) After complete combustion in the IKA C 3000 isoperibol calorimeter, the cover was automatically re-opened again.

m) Took out the decomposition vessel from calorimeter and pinned the knob to release excessive oxygen content.

n) Open the lid decomposition vessel, then checked the condition of cotton thread and sample fuel. (Make sure the cotton thread completely burnt and no fuel sample left).

o) The value of calorific value appeared on screen display with graph.

p) Step a) to o) were repeated for 3 times for average reading in each fuel blends.

Prepare a crucible and weight balance to measure the fuel blends. Make sure all the apparatus is in dry condition, clean and wipe all the apparatus by using tissue and acetone properly by following steps.

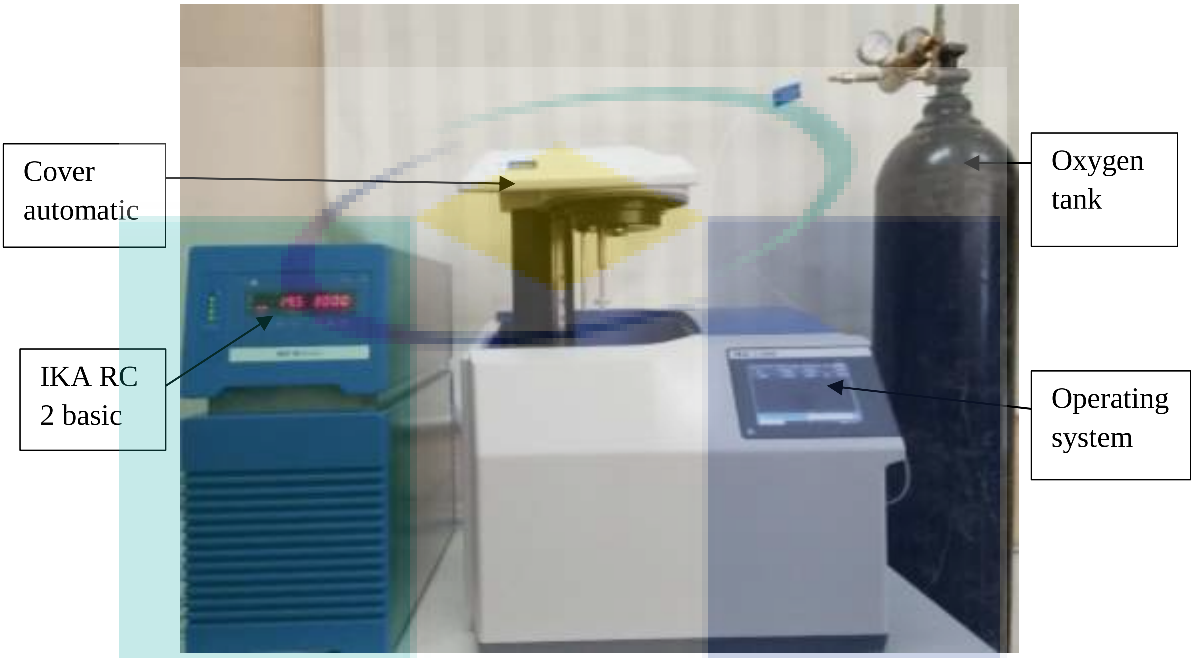


Figure 3.5 IKA C 3000 isoperibol calorimeter

Figure 3.6 IKA organizer

3.4.2 Kinematic viscosity

The laboratory equipment used to measure density and dynamic viscosity is the Stabinger Viscometer SVM 3001 from Anton Parr as shown in Figure 3.7. The SVM 3001 standard meets ASTM D7042 for dynamic viscosity, as well as ASTM D4052 for density. The kinematic viscosity was directly calculated from dynamic viscosity and density measured from SVM 3001. Equation 3.1 shows kinematic viscosity calculated from dynamic viscosity and density of the fuel blends as follows;

$$Kinematic\ Viscosity\ \left(\frac{mm^2}{s}\right) = \frac{Dynamic\ viscosity\ (mPa.s)}{Density\ (\frac{g}{ml})} \tag{3.1}$$

The features have a wide temperature range from -60°C to +135°C. All apparatus needs to be rinsed with toluene to clean the excessive mixture inside magnetic particle trap before any sample to be taken. The kinematic viscosity procedure are as follows:

a) The Stabinger Viscometer SVM 3001 was switched on.

b) Key in the sample name, repeated mode and temperature at the ‘Quick Setting’ channel in parameter operation.

c) The sample fuel blends were sucked by using a 10ml syringe.

d) Put the syringe into the knob that attached at magnetic particle trap.

e) Insert the sample fuel blends into the knob, and sample fuel blends will flow in hose.

f) Keep inserting the fuel blends until the remark, which was directly connected to the waste bottle.

g) Start the parameter operating with filled input data.

h) Wait until ‘Prewetting’ appears on the display.

i) Fill another 1ml into the magnetic particle trap.

j) Wait until the process complete.

k) The test was repeated with other sample fuels from steps a) to j).

Figure 3.7 Viscometer SVM 3001

3.5 Experimental setup

3.5.1 Diesel engine test model

In this study, the test engine model used was the YANMAR TF120M, a single cylinder diesel engine which was set up in the Power Engine Laboratory (PEL) of Universiti Malaysia Pahang (UMP) as shown in Figure 3.8. This research diesel engine consists of a direct injection with four-stroke, natural aspirated, and a water-cooling system. The test engine does not undergo any modification. Table 3.4 shows the detail specification of the test engine.

Table 3.4 Engine specifications

Descriptions	**Specifications**
Engine model	YANMAR TF120M
Engine type	Single cylinder, four-stroke
Bore X stroke (mm)	92 X 96
Displacement (L)	0.638
Injection timing	17° BTDC
Compression ratio	17.7
Continuous output	7.83 kW at 2400rpm
Rated output	8.95 kW at 2400rpm
Cooling system	Water cooled

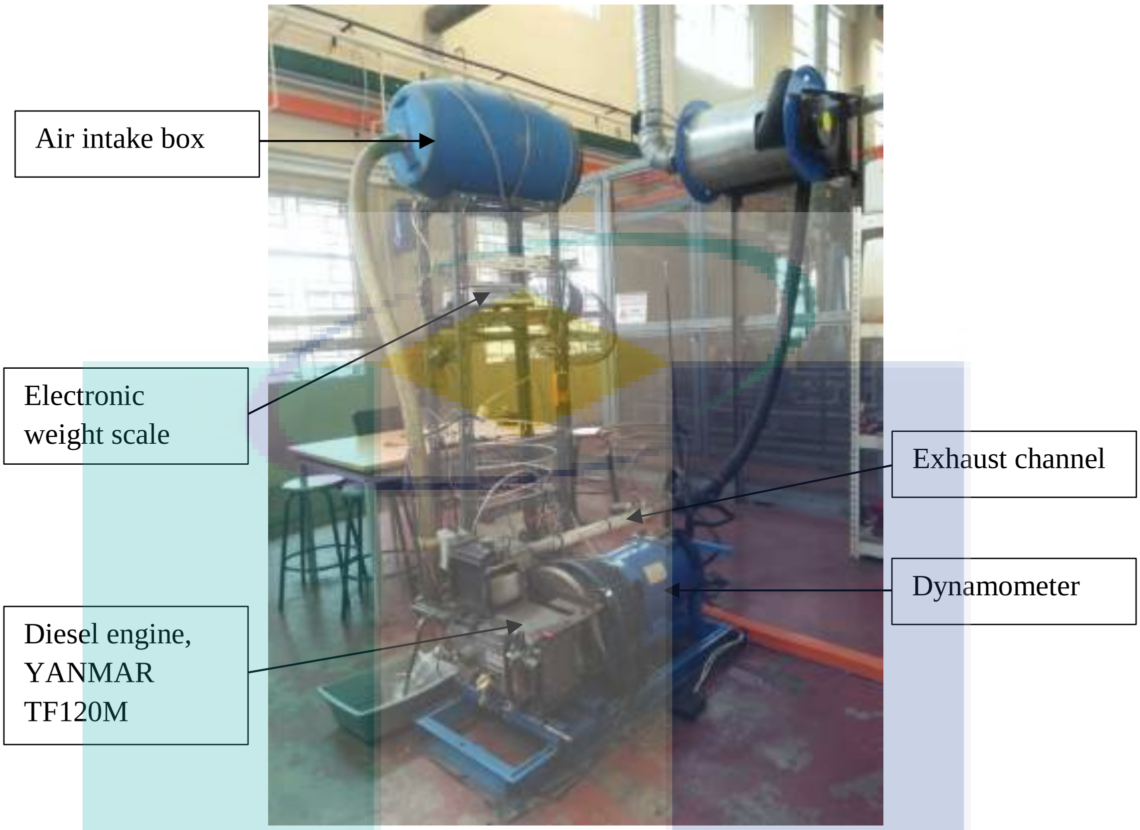


Figure 3.8 Power Engine Laboratory (PEL)

3.5.2 Engine test and equipment

The engine fuel system consists of a 4 litres tank which has one hose for fuel to flow into the engine during the experiment. The schematic diagram of the experimental setup as shown in Figure 3.9. The engine was fixed on a stable stand and loaded by a 15-kW eddy current dynamometer, supplied by Focus Applied Technologies BD-15 kW as shown in Figure 3.10. The details of dynamometer are tabulated in Table 3.5. The dynamometer of maximum electric power output of 15kW power was mounted in spherical bearings and fitted directly to the test engine to measure the engine brake torque. Consequently, the engine performance data collect, monitor and control by dyno controller Dynomax 2000, that connected from dynamometer to adjust the rpm, engine load and torque. The brake torque was measured by using a S-type load cell force sensor (Zemic model H3-C3-500Kg-3B). The output power of the dynamometer was consumed as heat at the resistor bank. The test rig provides a facility to measure the engine performance at different operating conditions of engine load and engine speed. The engine brake power was calculated by measuring both brake torque and engine speed. The speed was measured using the Hall Effect proximity sensor (AOTORO SC12-20 proximity sensor, type PNP-NO, M12 4-24VDC, and 20mA), which was fitted to the coupling on a device breaking. In addition, the fuel mass flow rate was measured by recording the time required to consume a specific mass of the fuel on a digital weight scale CAS (model TCS-6 up to 6 kg) as shown in Figure 3.11. The ambient air temperature, exhaust gases temperature and fuel temperature were measured using a thermocouple logger (model PicoLog TC-08 USB), for this purpose, three K-type thermocouple probes were installed.

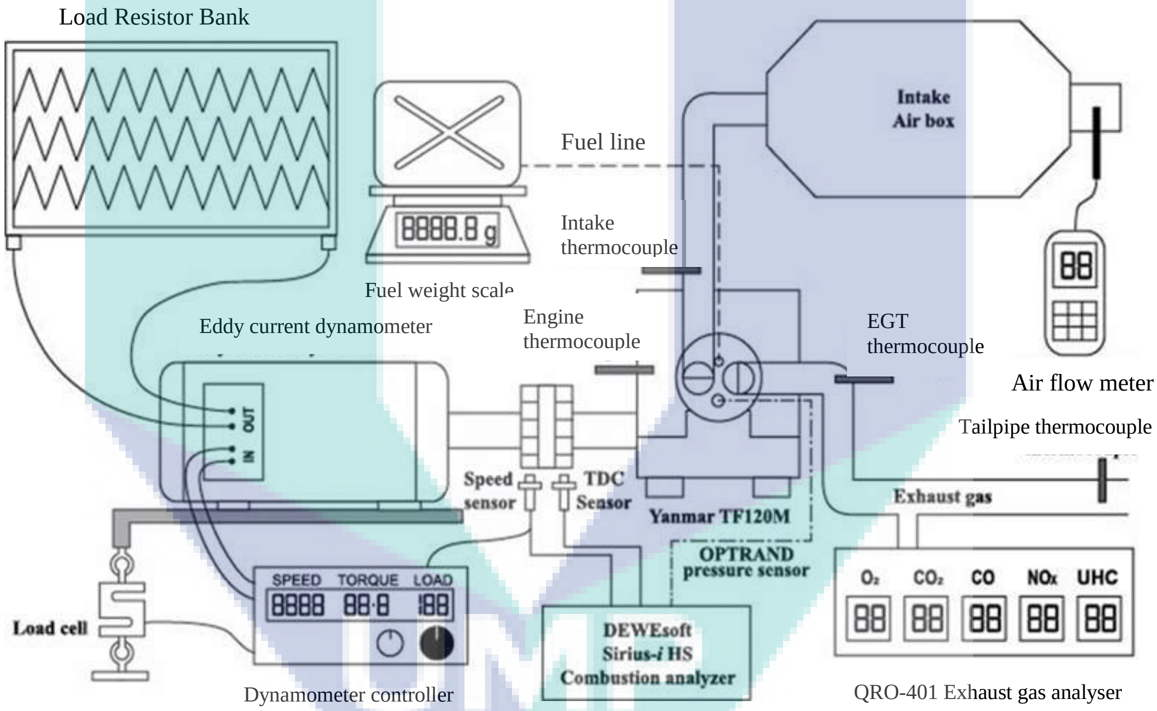


Figure 3.9 Schematic diagram of engine testing

Figure 3.10 Dynamometer

Table 3.5 Dynamometer characteristic and specification

Dimension	L x W x H (mm)	1200 x 490 x 400
	Weight	65 kg
Power input	Voltage	220 AC
	Frequency	50 Hz
	Current draw	4A maximum
Dynamometer power	Mechanical power	15,000 W
	Torque	60 Nm
	Speed	2400 rpm
	Electrical power	7500 W maximum
	Voltage output	300 V
	Current	40 A

Figure 3.11 Electric weight scale, CAS

Furthermore, the in-cylinder pressure was measured by a cylinder pressure sensor Optrand fibre optic transducer (model Auto-PSI C82294-Q), pressure range up 3000 psi, and sensitivity ~ 2.63 mV/psi) was mounted directly to combustion chamber. In addition, another Hall Effect proximity sensor (AOTORO SC12-20 K) was installed to precisely locate the piston top dead center (TDC) position was mounted on the engine flywheel, which was used to measure the crank angle position at every 0.1°CA resolution. Both signals from pressure output charge of the transducer and proximity sensor was converted from analogue data to digital data, and amplified using a data acquisition unit (DAQ) DEWESoft model SIRIUS i-HS (16-bit HI Speed ADC with 1ms/S @ 5 V), controlled by DEWESoft X2 combustion analyser software as shown in Figure 3.12. The combustion data was interpreted per cycle, around 200-300 cycle of data for every fuel blends test. The timing in crank angle degree (CAD) during combustion was then recorded by the crank angle sensor. The clearance between crank angle sensor tip and trigger wheel was calibrated to maximum 3mm and was adjusted to enhance the effectiveness of the piston top dead center (TDC). Additionally, to measure the exhaust emission, such as CO, CO_2 and NO_x, the automotive emission analyser QRO-401-5 (QRO Technologies) was used as shown in Figure 3.13. Further specification of gas analyser is tabulated in Appendix A. The parameters analysed and measured in this research experiment were recorded and discussed in regards to thermo-physical properties as well as stability, combustion characteristics, engine performances and exhaust emissions of a tri-fuel blends.

Figure 3.12 DEWESoft DAQ model SIRIUS i-HS

Figure 3.13 Gas analyser model QROTECH-401

In this research, diesel engines run fuel blends, DF, B100, D85-B10-PE5, D80-B10-PE10, D75-B10-PE15, D85-B10-HE5, D80-B10-HE10 and D75-B10-HE15 in various engine load, 0 Nm, 7 Nm, 14 Nm, 21 Nm and 28 Nm, at constant engine speed 1800 rpm. The selective engine speed with constant 1800 rpm is due to the BSFC and power has the better performance at 1800 rpm as shown in Appendix B. In additions, YANMAR TF120M engine had the highest BTE at 1800 rpm (Rashed et al. 2016). This experiment was repeated 3 times to ensure that the data collected was accurate and validated. Also, before the diesel engine was run with test fuel, DF was used to warm up the engine for about 10 minutes to stabilize the tri-fuel blend operating system. Finally, at every test fuel change, the engine was flushed with DF to pre-empt the waste of fuel blends.

3.6 Experimental design and statistical analysis

In experimental design, a standard RSM modeling has been applied to study the modelling and analysis of the response variables at various engine loads in order to obtain the engine characteristics that work on fuel blends. The experimental design is not only provide the individual effects of BSFC and BTE with engine loads, but also their interactions with the minimum number of experiments to achieve the optimum conditions by using Design Expert 7. In addition, RSM includes both mathematical and statistical techniques to describe the effect of parameter interactions in the response when varied simultaneously. The more reliable way to evaluate the quality of the model fitted is by the application of analysis of variance (ANOVA). ANOVA was used to verify model adequency which provides numerical information about *p*-value. The factors with a *p*-value greater than 0.05 were considered to be active, while the factors with a p-value less than 0.05 were held constant in the following experiments (Hirkude and Padalkar 2014). Subsequently, another set of two-level fractional factorial experiments combined with certain number of center and axial runs was conducted to construct a second-order regression model of the response as a function of the active factors. An optimization path was generated from the model and a set of experiments was conducted along the path to obtain the optimal response (Fang et al. 2015).

In this analysis the RSM was designed for two factors-three levels of historical data; (i) RSM for 1-pentanol-biodiesel-diesel tri-fuel blends, and (ii) 2-ethyl 1-hexanol-biodiesel-diesel tri-fuel blends were designed separately. The independent variables, engine load (A) and percentage of alcohol in fuel blends (B) was also taken as input parameters. The engine loads (denoted as load) varied at 5 levels from 0% to 100% in steps of 25%. The percentage of alcohol in fuel mixture (denoted as fuel) also varied at 3 levels, (D85-B10-PE5, D80-B10-PE10, D75-B10-PE15) and (D85-B10-HE5, D80-B10-HE10, D75-B10-HE15) respectively. The response (Y) for BSFC and BTE was evaluated, while the design matrix contains 15 runs of experiments. The experimental readings were fitted to the second order polynomial equation by the design expert software. A multiple regression analysis was carried out to obtain the coefficients and equations which was used to predict the responses. Using a statistically significant model, the optimum blend ratio between parameters and responses was obtained. The optimum value of the input parameters was then obtained by using a desirability approach for the designed RSM.

3.7 Uncertainty analysis

An uncertainty analysis was used to achieve the accuracy and standard of data of the experiments. Errors and uncertainties in the experiment from the instrument can affect the result. A list of instruments used for measuring various parameters and the percentage of uncertainties are presented in Table 3.6. the instrumental uncertainties for computed parameters are comprising CO, CO_2 and NO_x are calculated using propagation of the uncertainties of relevant measurable parameters as in Equation 3.2 and 3.3. as for the total uncertainty of computed parameters and measure parameters such as BSFC, BTE, and heat release rate are calculated based on root mean square of experiment data uncertainty and instrumental uncertainty. General formula for uncertainty propagation.

$$Y = X_1 \, x \, X_2 \, x \, X_3 \ldots . X_n \tag{3.2}$$

$$|\Delta Y|^2 = \sum_{i=0}^{n} \left[\frac{\delta Y}{\delta X_i} \, x \, \Delta X \right]^2 \tag{3.3}$$

Table 3.6 List of instrument and the percentage of uncertainty

	Measurement	± Uncertainties	Unit
Gas Analyser	CO	±0.1	vol %
QRO-401 (3 gases)	CO_2	±0.15	vol %
	NO_x	±0.1	ppm
Dynamometer	Brake power	±0.4	kW
Calculation	Heat release rate	±0.4	J/CA deg.
Calculation	BSFC	±1	g/kW.h
Calculation	BTE	±1	%

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

The purpose of this chapter is to verify that experimental process on the methodology or the flow work is come out with the results, analysis and discussion. The result included properties test of fuels blends at different ratios, and engine test for combustion characteristic, engine performance and exhaust emission. Mainly, this research focuses on the experiment discussion and comparing majority results with net diesel fuel and biodiesel. All the results of the experiment are recorded and analysed in this chapter.

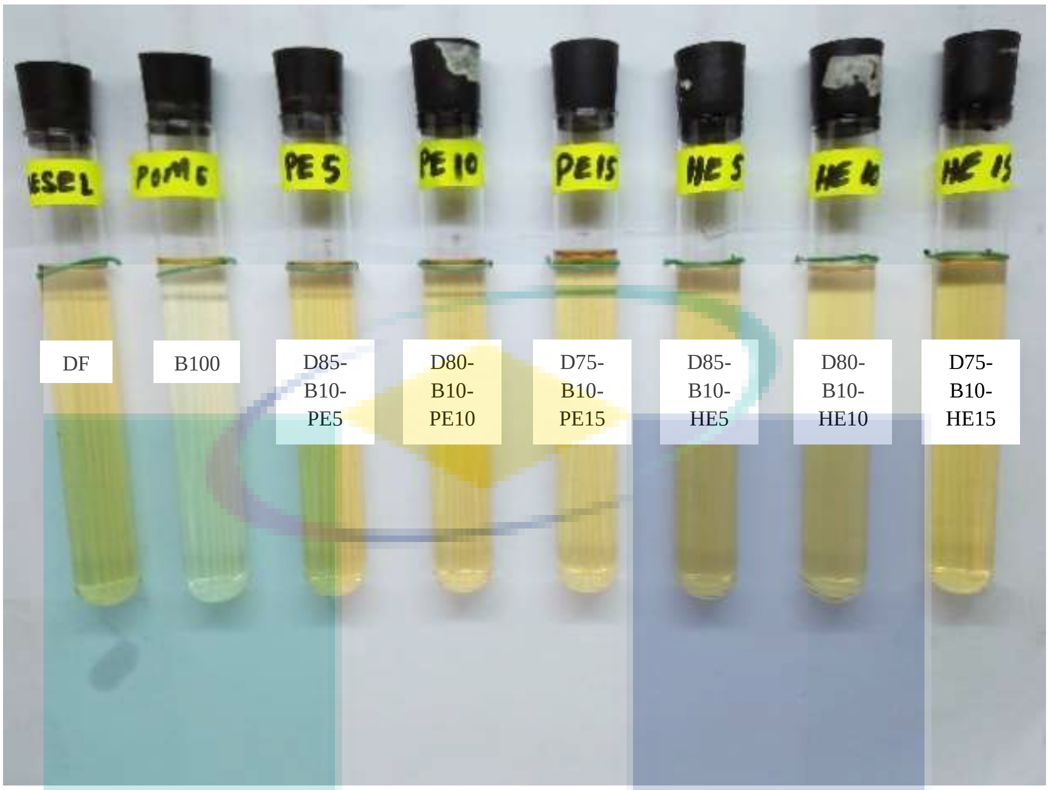
4.2 Stability behaviour and thermo-physical properties

The tri-fuel blends stability observation or measurement and thermo-physical properties of the long-chain alcohol-biodiesel-diesel tri-fuel blends were the first objectives of this research. The stability of a tri-fuel blend are the most important criteria to be confirmed before continuing to the next step. This is to determine whether the tri-fuel blends can be safely run in the engine or not. The thermo-physical properties are the next step after stability testing before deciding to run the fuel blends in the engine.

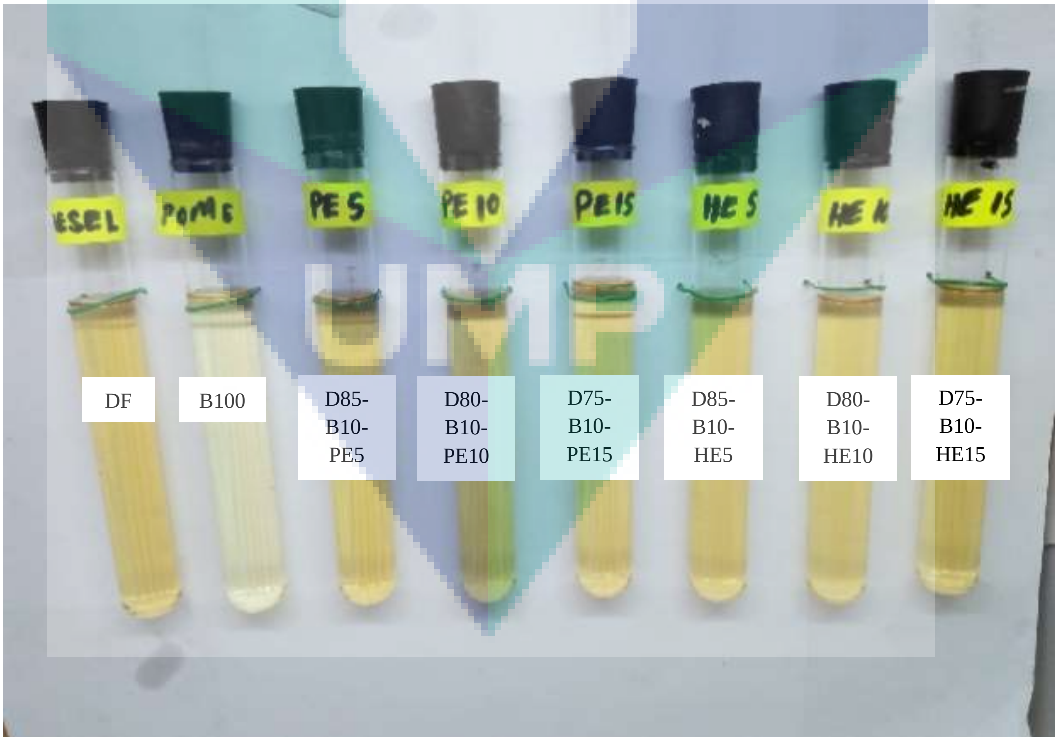
Fuel stability observation is the first step to ensure the tri-fuel blends are safe to be used for engine testing. In the tri-fuel blends stability behaviour observation, the presence of the phase separation indicates that the fuel blends have poor miscibility and high potential to be retarded during engine operation. Other than that, the instabilities will impair the engine performance due to fuel filter plugging, injector fouling, and deposit formation in the engine combustion chamber.

Referring to the stability observation in Figure 4.1, the images of long-chain alcohol-biodiesel-diesel tri-fuel blends of D85-B10-PE5, D80-B10-PE10, D75-B10-PE15, D85-B10-HE5, D80-B10-HE10, and D75-B10-HE15 were taken at 1 minute after blending, 1 hour, 1 day and 10 days after the blending process. The results show all fuel blends did not have any phase separation even after a month, which indicates that the fuel blends stability was very high. The conclusion from the stability observation is that the long-chain alcohol-biodiesel-diesel tri-fuel blends can be employed in a diesel engine. The reason for its greater stability compared to short-chain alcohol fuel blends is due to the long-chain alcohol that consists of more carbon and hydrogen number, which required the bonding between molecules to be tighter, and less energy to break the bonds, thus making the mixture were stable. Moreover, the stability of POME is good due to the presence of a higher concentration of saturated fatty acids. Furthermore, the stability observations were extended up to 2 month and observation results were still the same, which there were no visible separation. The results were agreed by Sivalakshmi and Balusamy (2011), which concluded that long-chain alcohol has a high cetane number and better miscibility when added with diesel.

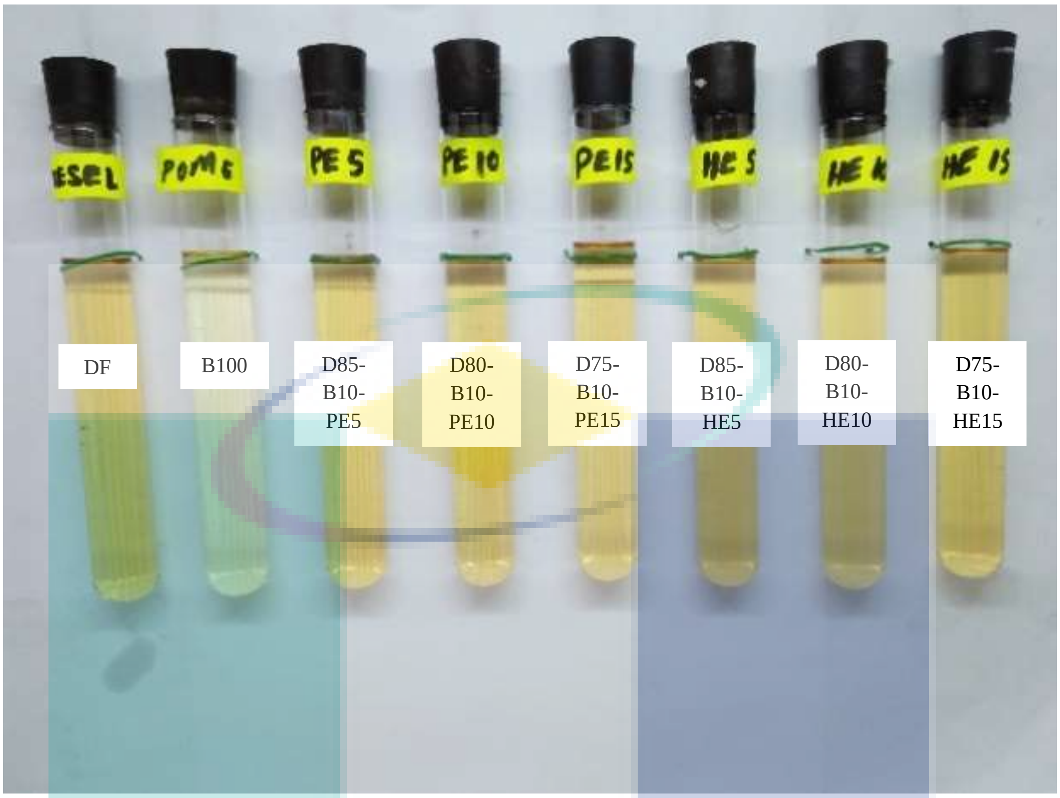
According to previous research, the fuel blends phase separation occurrence depends mainly on two factors; (i) the temperature, and (ii) water content. For example, the emulsion fuel has a high probability to show phase separation, due to the water that has a high density compared to diesel fuel (Lapuerta et al. 2007).



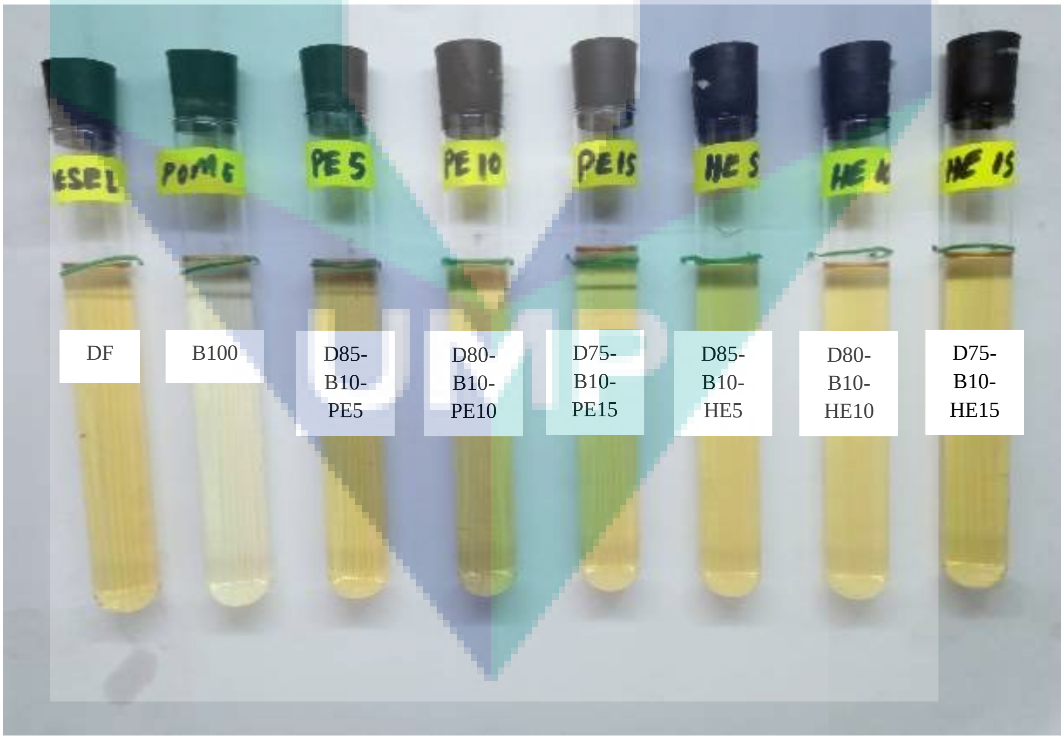
1 minute



1 hour



1 day



10 days

Figure 4.1 Observation on stability for DF, POME and all tri-fuel blends

Table 4.1 Distance of sedimentation after blending process

Test fuel	Distance of sedimentation of test fuel at specific time (m)														
	Minute					Hour					Day				
	1	2	3	4	5	1	2	3	4	5	2	4	6	8	10
DF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
B100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D85-B10-PE5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D80-B10-PE10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D75-B10-PE15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D85-B10-HE5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D80-B10-HE10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 4.1 shows the sedimentation of test fuel after blending process at specific time, in minutes, hours and days. From the table shows, it can be concluded that there is no any phase separation between diesel-biodiesel and long-chain alcohol. Abdullah et al. (2019) also give the same reason, where the POME and long-chain alcohol are better miscibility and consist higher number of carbon and hydrogen to become a strong bond.

4.3 Thermo-physical properties

This step is to find the thermo-physical properties of the pure diesel fuel, crude POME biodiesel, and the tri-fuel blends. This is to ensure whether the tri-fuel blends can safely be tested in the engine. Moreover, the thermo-physical properties consist of five properties; (i) the fuel calorific value, (ii) cetane numbers, (iii) fuel density, (iv) dynamic viscosity, and (v) kinematic viscosity. The results of thermo-physical properties for DF is B100, D85-B10-PE5, D80-B10-PE10, D75-B10-PE15, D85-B10-HE5, D80-B10-HE10 and D75-B10-HE15 as shown in Table 4.2.

Table 4.2 Thermo-physical properties of fuel blends

	DF	B100	D85-B10-PE5	D80-B10-PE10	D75-B10-PE15	D85-B10-HE5	D80-B10-HE10	D75-B10-HE15
Calorific value (MJ/kg)	45.82	39.72	44.64	44.27	43.41	44.81	44.49	44.24
Cetane number	55	57.3	53.48	51.3	49.98	53.64	52.05	50.46
Density (kg/m^3)	821.0	858.8	823.0	821.9	820.6	824.4	824.3	823.8
Dynamic viscosity (mPa.s)	2.89	3.99	2.86	2.76	2.65	2.98	2.95	2.94
Kinematic viscosity (mm^3/s)	3.52	4.65	3.47	3.35	3.23	3.61	3.58	3.57

The equipment that was tested to measure the thermo-physical properties of long-chain alcohol-biodiesel-diesel tri-fuel blends were characterized strictly following the ASTM standard as mention in Table 3.3 before. Referring to Table 4.2 above, the calorific values of all tri-fuel blends are higher than B100 (crude POME) by 12.38%, 11.45%, 9.29%, 12.81%, 12.01%, and 11.38%, corresponding to D85-B10-PE5, D80-B10-PE10, D75-B10-PE15, D85-B10-HE5, D80-B10-HE10 and D75-B10-HE15. The calorific value increases as the percentage volume ratio of PE and HE increased in fuel blends. As such, the calorific value of fuel blends has an impact on the engine power output. Meanwhile, D85-B10-PE5, D80-B10-PE10, D75-B10-PE15, D85-B10-HE5, D80-B10-HE10, and D75-B10-HE15 has low density by 4.17%, 4.30%, 4.45%, 4.01%, 4.02%, and 4.08%, respectively compared to B100. The dynamic viscosity for D85-B10-PE5, D80-B10-PE10, D75-B10-PE15, D85-B10-HE5, D80-B10-HE10 and D75-B10-HE15 were decreased by 28.32%, 30.83%, 33.58%, 25.31%, 26.07%, and 26.32% than B100. The density and viscosity were decreased as a percentage volume ratio increased by 5%, 10% and 15% of PE and HE compared to B100. Conversely, the kinematic viscosity value was directly calculated from the dynamic viscosity to density and the results showed that the kinematic viscosity was reduced by 25.38%, 27.96%, 30.54%, 22.37%, 23.01%, and 23.23% respectively for D85-B10-PE5, D80-B10-PE10, D75-B10-PE15, D85-B10-HE5, D80-B10-HE10, and D75-B10-HE15 compared to B100.

The density of fuel influences efficiency of fuel atomization and combustion characteristics was due to the engine output power that causes from a different mass of injected fuel. Density can be related with viscosity, which viscosity is inverse to the density, so that attributed to the reduction of kinematic viscosity of the tri-fuel blends owing to its better atomization efficiency (Imdadul et al. 2015). While the higher viscosity of tri-fuel blends compared to DF was because the density of biodiesel is higher than PE and HE, where B100 is 858.8 kg/m^3, PE and HE are 810.9 kg/m^3 and 815.2 kg/m^3, respectively (Al-Jimaz et al. 2004).

Similarly, the cetane number was also reduced when referring to D85-B10-PE5, D80-B10-PE10, D75-B10-PE15, D85-B10-HE5, D80-B10-HE10, and D75-B10-HE15 by 6.67%, 10.47%, 12.77%, 6.39%, 9.16%, and 11.94% compared with B100. The overall results from the thermo-physical properties measurements indicated that the long-chain alcohol provides more oxygen and stability. Many know that in general, biodiesel has high density, dynamic viscosity, kinematic viscosity, and cetane number but low calorific value. Therefore, fuel with high viscosity causes poor fuel atomization, thus more energy is needed to pump the fuel. In order to address the biodiesel high viscosity problem, the biodiesel was blended with long-chain alcohols, such as PE and HE to improve its fuel properties and stability. This trend was supported by Babu and Anand (2017), who both investigated the effects of n-pentanol and n-hexanol fuelled with biodiesel-diesel fuel blends on diesel engines. They found that the fuel blends density was reduced by 1.58% and 1.54% for B90-D5-P5 and B90-D5-H5 compared to biodiesel. The reduction density of biodiesel-diesel-n-pentanol blends and biodiesel-diesel-n-hexanol blends with increasing the concentration volume of n-pentanol and n-hexanol, the density of n-pentanol and n-hexanol are also lower than biodiesel.

4.4 Combustion characteristics (In-cylinder pressure and heat release rate)

The combustion characteristics include the analysis of 5%, 10% and 15% volume concentration of PE and HE on the combustion in-cylinder pressure and HRR. The in-cylinder pressure and HRR against CA graphs were plotted in various engine loads. The engine operated in low engine load from 0% to 25%, medium engine load 50%, and high engine load of 75% to 100%, at a constant engine speed of 1800 rpm. Basically, this subchapter will cover the second objective which is to investigate the combustion characteristics, engine performances and exhaust emissions of long-chain alcohol-biodiesel-diesel tri-fuel blends.

In-cylinder pressure data are interpreted to understand the complete combustion process and events occurring in the combustion chamber. The relationship between in-cylinder pressure and crank angle (CA) could also represent the actual engine performance. The in-cylinder pressure graph could provide a gross indication related to the engine knock, the location of peak pressure and the peak pressure value. Basically, the performance in combustion characteristics are affected by thermo-physical properties, fuel ratio, types of fuel and types of engine. In addition, HRR analysis is the most helpful approach to a better understanding of combustion mechanisms. HRR analysis offer to expedite the distinguishing proof of SOC timing and contrasts in the rates of combustion.

The variation of in-cylinder pressure and HRR at various engine loads for DF, B100 and tri-fuel blends of PE and HE at 1800 rpm constant engine speed are demonstrated in Figure 4.2 to Figure 4.7. In overall observation, the in-cylinder peak pressure of long-chain alcohol-biodiesel-diesel tri-fuel blends increase significantly as the load increased. At 0% engine load, the in-cylinder pressure was decreased by 0.18%, 1.89%, as well as 3.42% and 3.19% for D80-B10-PE10, D75-B10-PE15, D85-B10-HE5, and D75-B10-HE15 respectively. Nevertheless, D85-B10-PE5 and D80-B10-HE10 slightly increased by 1.03% and 0.86% compared to DF for PE and HE at peak pressure. In physical effect of lower in-cylinder pressure, tri-fuel blend at low engine load is due to low in-cylinder temperature, thereby making the lowest values in density and kinematic viscosity of tri-fuel blends. It can be noticed at low engine loads, the maximum combustion pressure for DF is higher than long-chain alcohol-biodiesel-diesel tri-fuel blends. Besides that, at low engine load, the addition of alcohol increased the latent heat of evaporation of fuel blends and delays combustion further into expansion stroke, both affected reduce peak pressure in-cylinder pressure. The reduction of in-cylinder pressure of PE and HE fuel blends is due to lower density energy which gives lower premixed combustion and gas pressure in the cylinder. Moreover, as explained by Fattah et al. (2014), the phenomena was also contributed to the higher molecular weight of biodiesel resulting in poor atomization before the premixed combustion phase.

In addition, it shows the peak in-cylinder pressure increases due to more fuel that was injected at a high engine load. The higher peak pressure noticed for D85-B10-PE5 with increments by 1.08% in comparing with DF, due to rapid combustion of accumulated fuel as the temperature of combustion increases at a high load. However, peak pressure for other fuel blends were reduced by 2.91%, 0.66%, 0.54%, 5.67%, and 1.60% for D80-B10-PE10, D75-B10-PE15, D85-B10-HE5, D80-B10-HE10, and D75-B10-HE15, respectively compared to DF, occurring at 100% engine load. The ignition delay was getting shorter with reduction of in-cylinder temperature, thus reducing NO_x emissions that are normally developing during high in-cylinder temperature. Conversely, the peak in-cylinder pressure for tri-fuel blends at high engine load was reduced due to higher in-cylinder pressure temperature that weakens the cooling effect of long-chain alcohol. In addition, early SOC that was detected was due to the advancement in fuel injection timing process of small droplets of injected fuel at a high injection pressure and high oxygen content leading to better combustion. Also, the maximum cylinder pressure that was increased within increasing the quality injected fuel was due to a rich mixture that was formed inside the chamber, which burns more rapidly in early premixed combustion. However, the increases in ignition delay gave some advantages, such as increased fuel burns in premixed mode, leading to peak pressure in-cylinder which also increased. Similar research was done by Imtenan et al. (2015), on the evaluation of n-butanol as an oxygenated additive to improve combustion characteristics-emission-performance of DF with *Calophyllum Inophyllum* biodiesel blends. It was found that higher in-cylinder pressure was due to lower viscosity and higher volatility of n-butanol, which is conducive for more fuel-air mixture during the ignition delay period, resulted in a higher premixed portion of combustion.

In general, referring to the figures, the HRR curves of all tri-fuel blends are similar to DF. At low engine load, HRR of D85-B10-PE5, D80-B10-PE10, D75-B10-PE15, and D80-B10-HE10 were increased by 16.71%, 9.27%, 8.0%, and 1.45%, respectively. However, HRR of D85-B10-HE5 and D75-B10-HE15 were slightly reduced by 9.12% and 4.17% compared to DF, and the peak HRR occurs at peak HRR. Since the long-chain alcohol-biodiesel-diesel tri-fuel blends have a low cetane number and high latent heat of evaporation, thus there is a high proportion of long-chain alcohol blends delayed of the SOC and lengthen the ignition delay. However, the increasing HRR shows a rapid phase of premixed combustion and followed by a slower phase of diffusion combustion. In addition, the decreasing cetane number of long-chain alcohol leads to the preparation of a large portion of fuel blends for rapid burning during the longer ignition delay.

In overall observation, HRR increases at high engine load compared to low and medium engine loads. HRR of PE fuel blends shows a higher value than HE fuels blends in various concentration. At 100% engine load, HRR was reduced by 3.37%, and 9.29%, for D85-B10-PE5 and D80-B10-PE10. However, the HRR of D75-B10-PE15 increased insignificantly by 0.43% compared with DF. The reason reduction for HRR is due to the high kinematic viscosity of B100. Other than that, the reduction of HRR in PE was due to the longer ignition delay that allows more fuels accumulation in the combustion chamber to released high heat during the premixed combustion phase. Also, the longer the ignition delay at PE was due to a cetane number of PE that is lesser than HE. While, the higher value of HRR for D85-B10-HE5, D80-B10-HE10, and D75-B10-HE15 was increased by 17.41%, 7.69%, and 31.98% respectively. Thus, the high HRR value indicates a better fuel-air mixing process, but when comparing HRR value between PE and HE, higher HE fractions in tri-fuel blends were noticeable. Therefore, the vaporization of blends promoted by mixing higher volatility fuel from HE. The higher engine loads resulted in a high temperature increase and high cylinder pressure for better fuel-air mixing, the higher flame velocity that causes in combustion to start early for the HRR during the premixed combustion period. Moreover, the increment HRR is due to oxygen that contains in long-chain alcohol, as well as a larger portion of fuel for rapid burning during the longer ignition delay. More so, the high latent heat of vaporization of PE and HE was affected by quenching effect and lower in-cylinder temperature, as well as the delayed of the maximum heat release rate (Suhaimi et al. 2018).

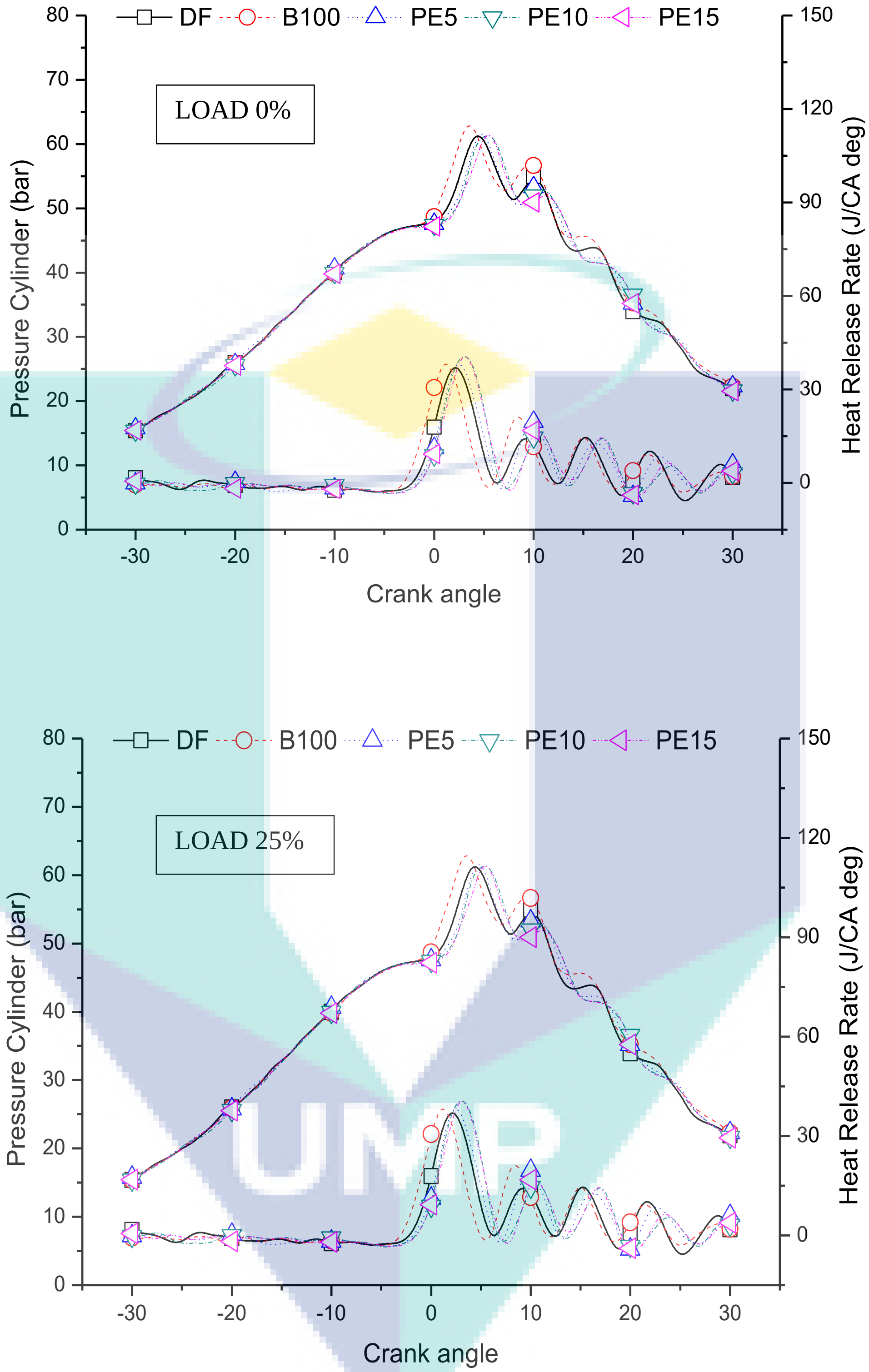


Figure 4.2 Variation of in-cylinder pressure and HRR for 0% and 25% engine load of PE

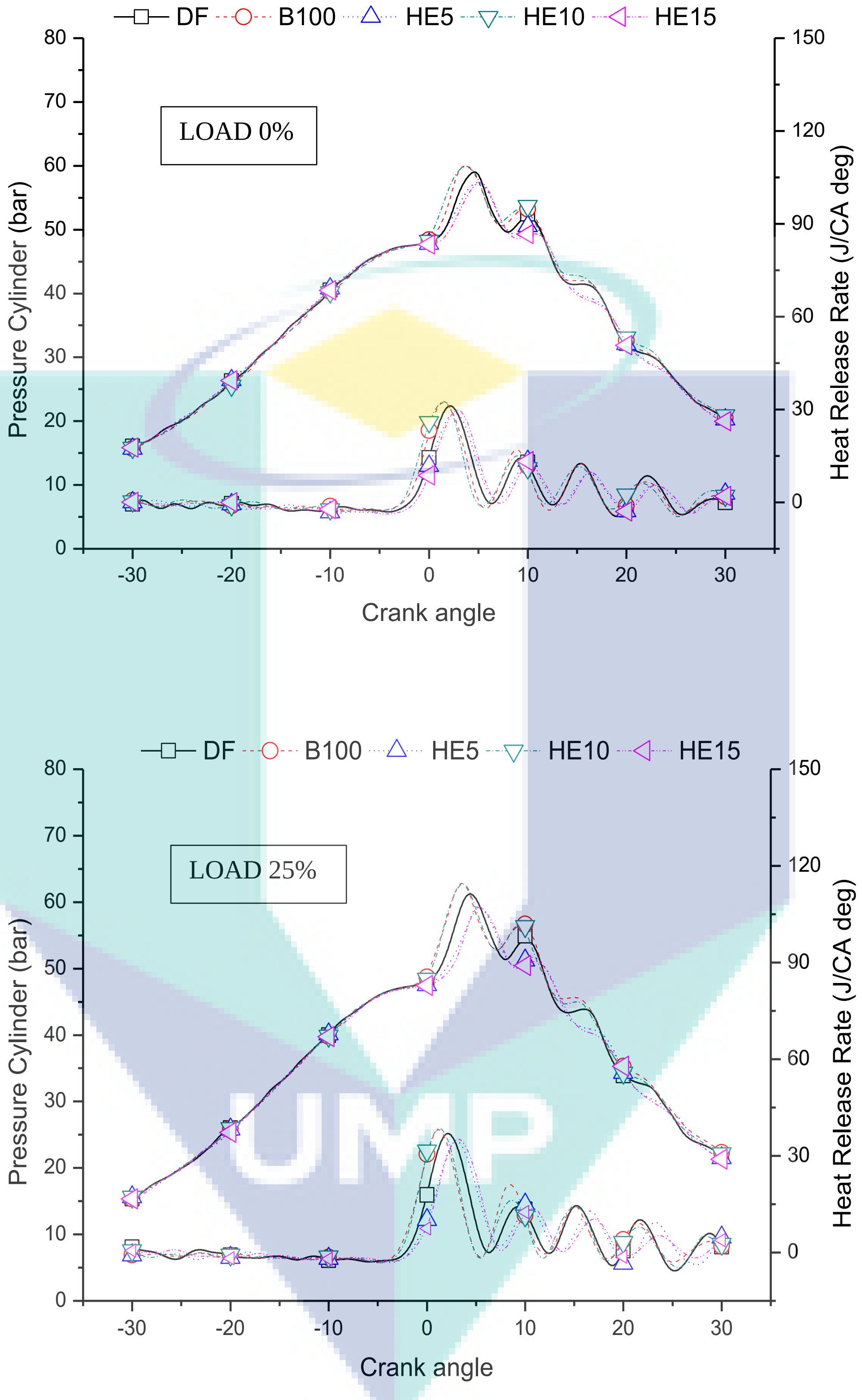


Figure 4.3 Variation of in-cylinder pressure and HRR for 0% and 25% engine load of HE

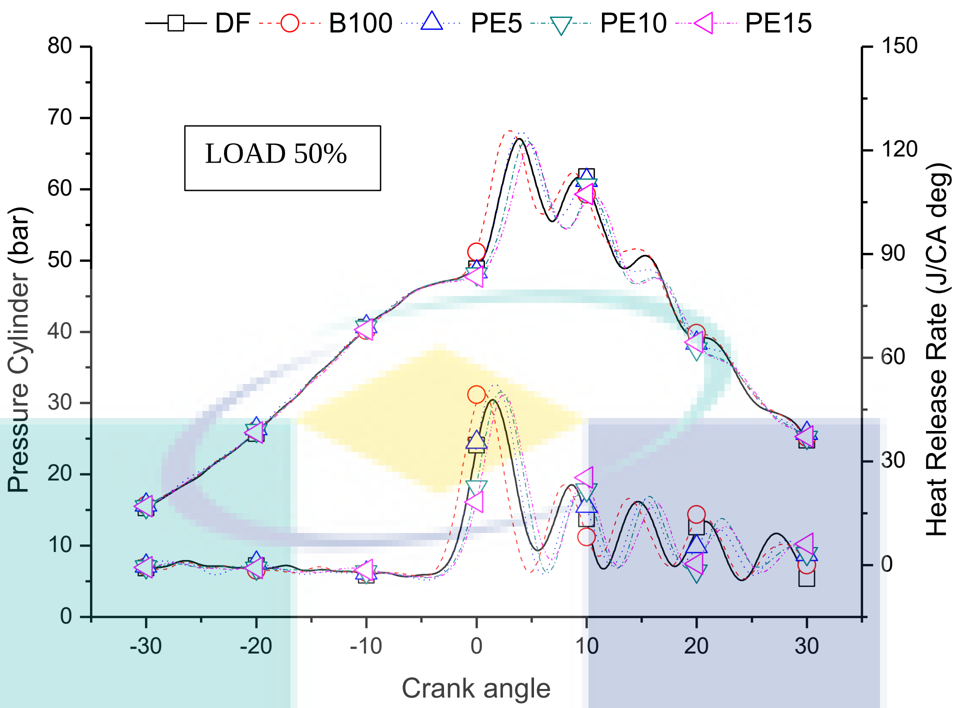


Figure 4.4 Variation of in-cylinder pressure and HRR for 50% engine load of PE

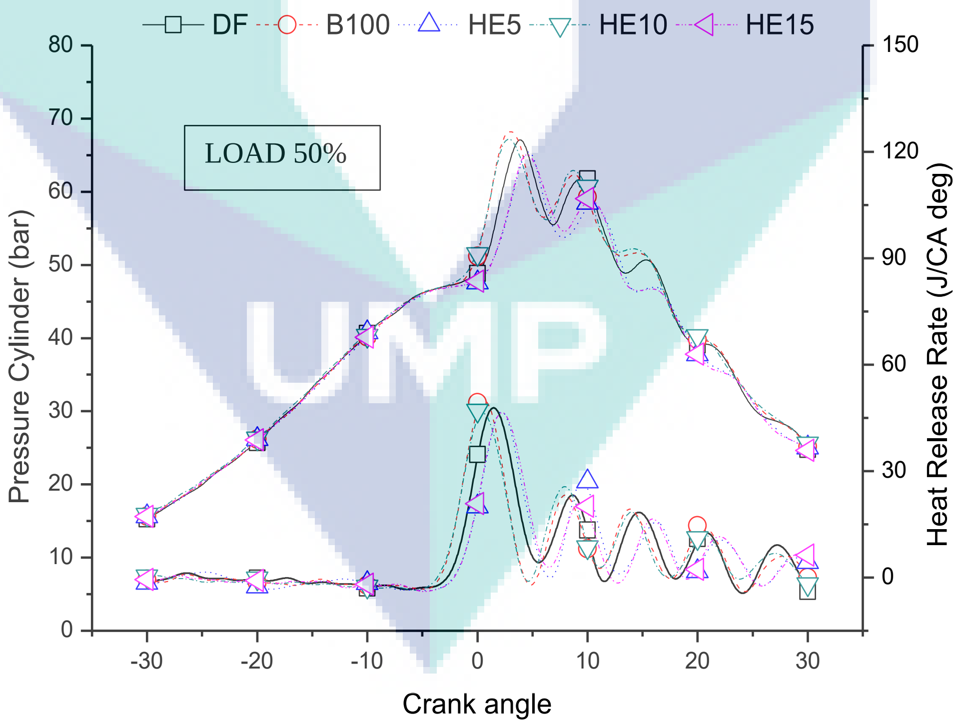


Figure 4.5 Variation of in-cylinder pressure and HRR for 50% engine load of HE

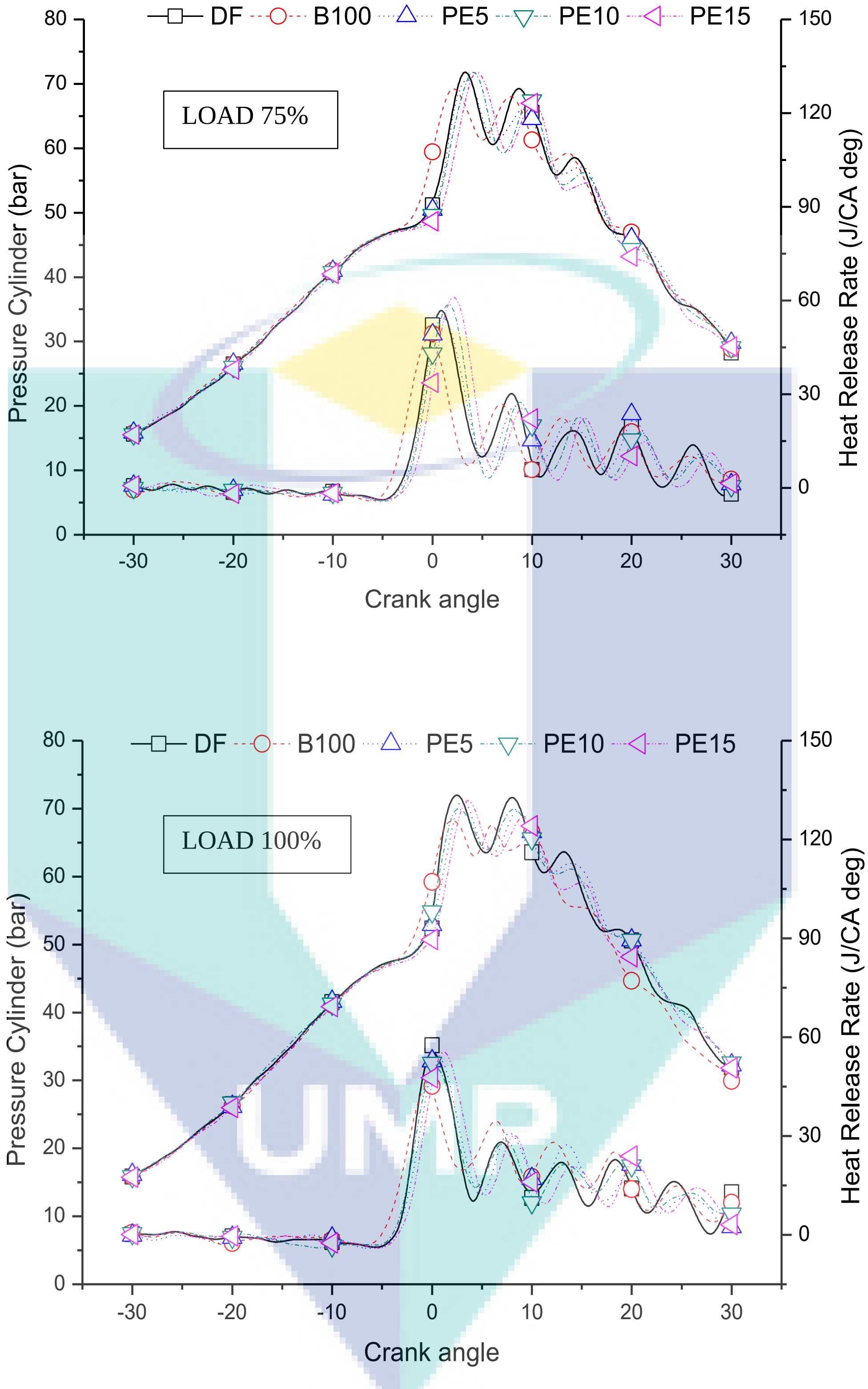


Figure 4.6 Variation of in-cylinder pressure and HRR for 75% and 100% engine load of PE

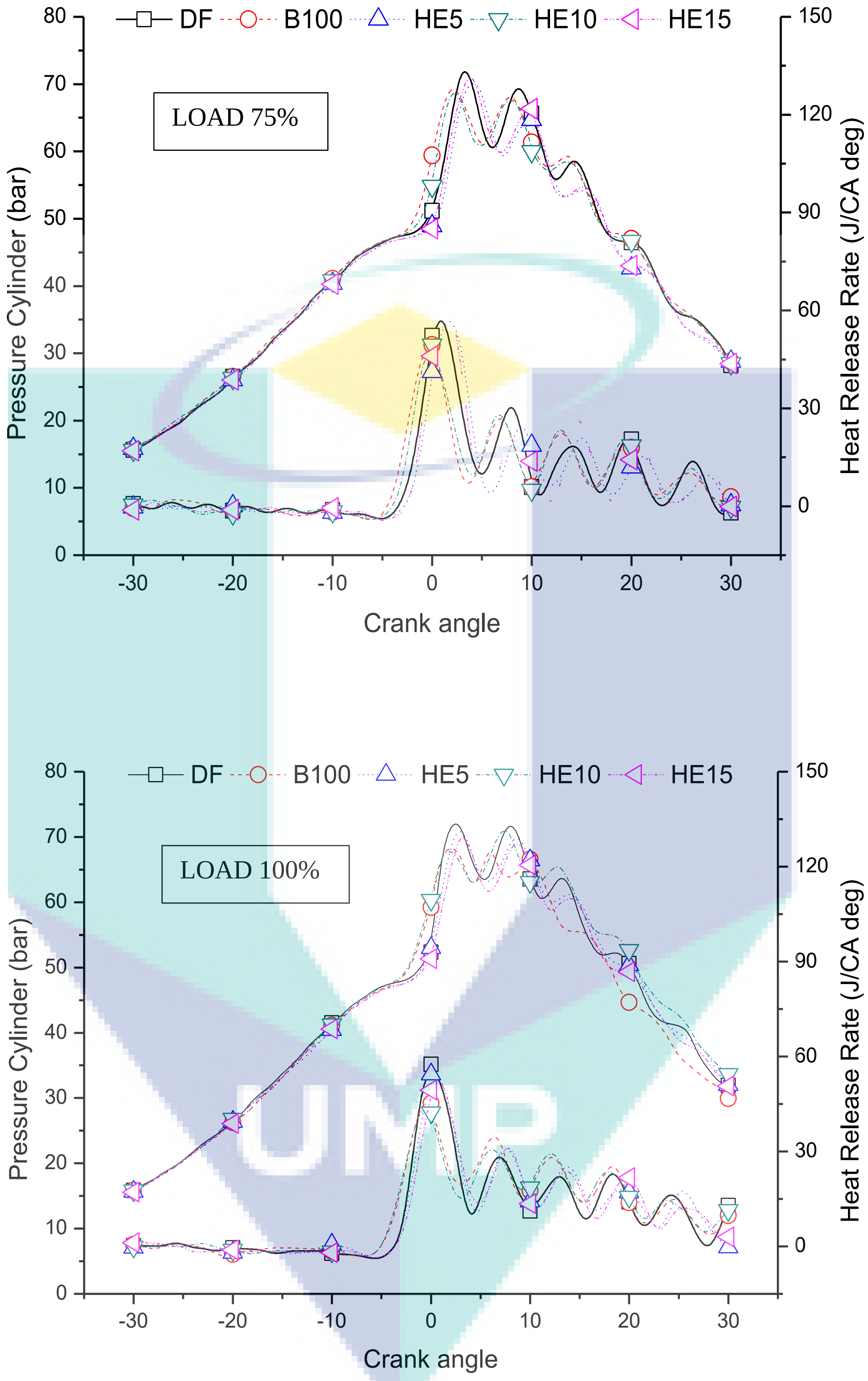


Figure 4.7 Variation of in-cylinder pressure and HRR for 75% and 100% engine load of HE

4.5 Engine performance

In an internal combustion engine, BSFC, BTE, brake power and torque are important in engine performances. The graph was plotted against engine loads, 0%, 25%, 50%, 75% and 100% at constant engine speed of 1800 rpm.

4.5.1 Brake thermal efficiency (BTE)

The brake thermal efficiency (BTE) of an engine indicates the efficiency of the fuel's chemical energy to transform into mechanical output. Factors that improve the efficiency is that is must have a higher calorific value and low viscosity.

Figure 4.9 shows trend of BTE for all fuel blends of PE and HE in comparison to DF and B100. All BTE increased rapidly with increasing of engine loads. In comparison to DF, the results reveal that BTE of B100, D85-B10-PE5, D80-B10-PE10, D75-B10-PE15, D85-B10-HE5, D80-B10-HE10 and D75-B10-HE15 were increased by 8.79%, 7.92%, 10.37%, 6.22%, 7.55%, 5.37%, and 8.78%, respectively at 100% engine load. In the class of tri-fuel the highest efficiency of BTE measured are D80-B10-PE10 and D75-B10-HE15 with 10.37% and 8.78% respectively, occurred at 100% engine load. Also, the BTE of the tri-fuel blends shows improvement due to the effect of long-chain alcohols when added to diesel and biodiesel. High oxygen content was formed in a long-chain alcohol-biodiesel-diesel tri-fuel blends, that leads to a better atomization (Campos-Fernández et al. 2012). The presence of oxygen molecules will improve the combustion, especially during the diffusion combustion, leading to increase of the efficiency in diesel engines. Moreover, a low cetane number of PE and HE also led to a prolong ignition delay, thus gaining more fuel burned during premixed combustion. Moreover, improved BTE of long-chain alcohol-biodiesel-diesel tri-fuel blends were attributed to the expanded accessibility of fuel bounded with oxygen and increases brake power, and improving the ignition quality. In additions, the increment of BTE is due to the higher calorific value and low kinematic viscosity, that required less quantity of fuel to be supplied. Others remark behind the high BTE for long-chain alcohol-biodiesel-diesel tri-fuel blends were the reduction in the heat losses by decreasing temperature at the beginning of combustion. Furthermore, the factor of high BTE was due to maximum HRR, which reduce the heat losses with lower in-cylinder pressure (Noguchi et al. 1996).

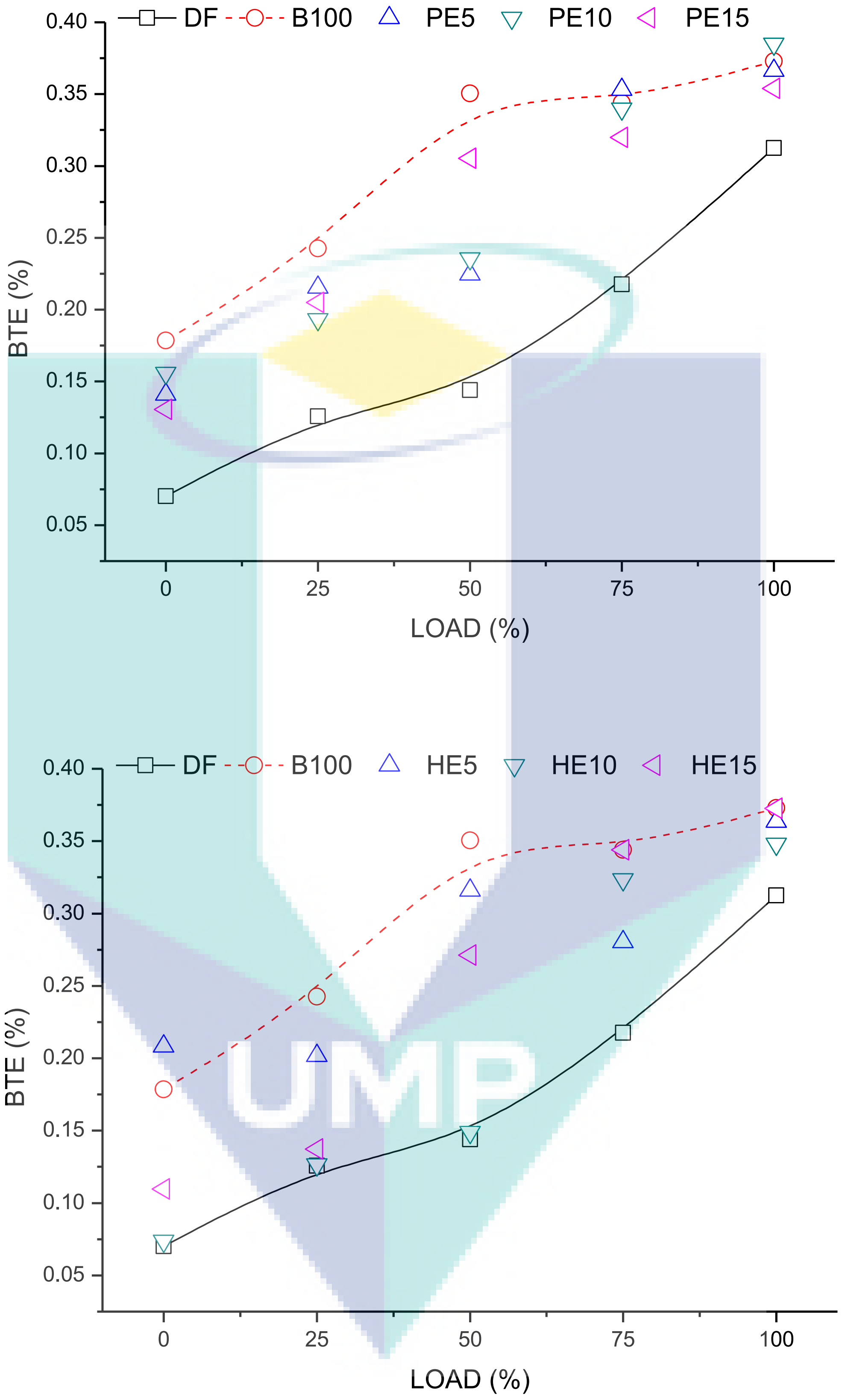


Figure 4.8 Variation BTE for PE and HE against various engine loads

4.5.2 Brake specific fuel consumption (BSFC)

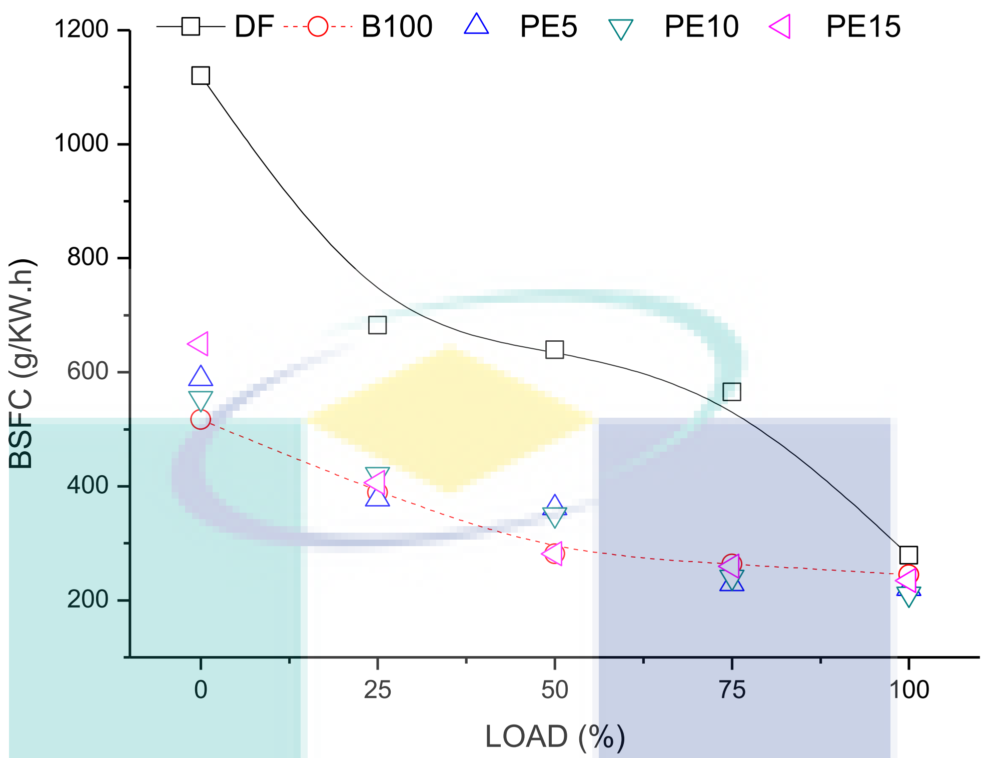
The brake specific fuel consumption (BSFC) indicates the quantity of fuel supplied to the engine per unit power production. The fuel consumption of an engine fuelled with biodiesel is affected by some operating conditions, such as speed, load, injection pressure and timing delay.

Figure 4.10 demonstrates BSFC, of each fuel with various engine loads. The overall of both PE and HE results show that BSFC continues to reduce from 0% to 100% engine load. The reduction of BSFC, is one of improvements in fuel blends, due to the usage of fuel into diesel engine is lesser during running in engine. More reduction in BSFC, means it's better for engine performance. In general, the BSFC reduced as the engine load increased.

This is a result of increasing fuel combustion efficiency in relation to increasing in-cylinder temperature at higher load. Highest value of BSFC can be observed at low engine load at 0% and 25% which can be indicated. There was a low in-cylinder temperature that leads to incomplete combustion and low combustion efficiency. The BSFC reduced by 6.49%, 11.73%, 13.75%, 8.72%, 11.51%, 9.01% and 12.19% for B100, D85-B10-PE5, D80-B10-PE10, D75-B10-PE15, D85-B10-HE5, D80-B10-HE10 and D75-B10-HE15 in comparison to DF at 100% engine load. In the class of tri-fuel the highest improvement of BSFC was D80-B10-PE10 and D75-B10-HE15 by 13.75% and 12.19% respectively.

The reduction of BSFC was due to the higher oxygen content in tri-fuel blends that lead to high amount of power supply during combustion. Therefore, the addition of long-chain alcohol leads to an increase in diffusion rates of fuel vapour inside the combustion chamber, thus promotes the preparation of air-fuel mixture before ignition and resulting in the reduction of BSFC. Besides that, the high latent heat of vaporization of PE and HE also contributes to low BSFC, which caused the cooling effect that reduce fuel consumption in the combustion chamber. In addition, lower density and calorific value of a tri-fuel blends improved the atomization between DF and long-chain alcohol, leading to better combustion. Moreover, the tri-fuel blends have a short ignition delay which leads to better combustion efficiency, thus effecting the reduction of exhaust emissions.

According to Devarajan et al. (2017) who have experimented with the addition of pentanol in biodiesel-diesel on analysis performance and emission, reported that BSFC for C90P10 and C80P20 (90% cashew nut shell + 20 pentanol) was reduced by 13.25% and 15.42% compared to DF. This is due to BSFC decreased with increase in pentanol content, owning to reduction in viscosity of fuel with addition of pentanol. Fuel with lesser viscosity aids the combustion as it mixes effectively with air in the cylinder during combustion. In additions, the density of fuel mixture increases with additional of pentanol, which subsequently reduced BSFC of fuel blends.



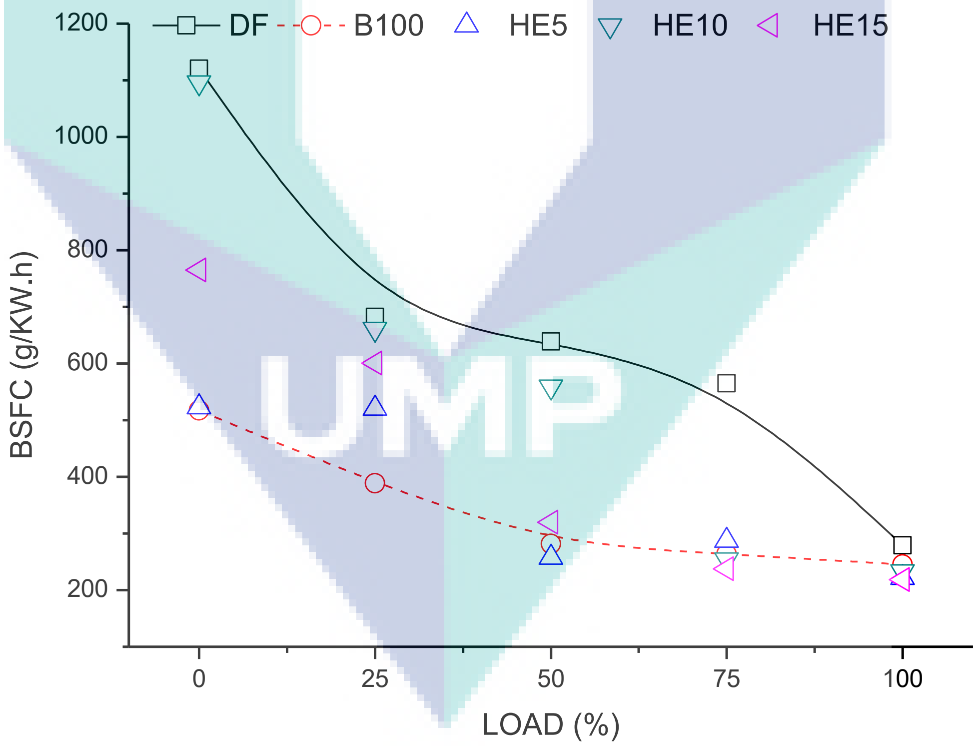


Figure 4.9 Variation of BSFC for PE and HE against various engine loads

4.5.3 Brake power and torque

The engine brake power and brake torque for different engine loads are shown in Figure 4.10 and Figure 4.11. This figure demonstrates that brake power and brake torque increased with the increase of the engine load. In general, no significant difference was noticed in the brake power and torque respectively among the tri-fuel blends, especially at low and higher engine loads. In comparison with B100, at 100% engine load, the brake power decreased by 0.63%, 1.68%, 2.32%, 8.12%, and 2.68% while the brake torque also increased by 0.62%, 1.65%, 2.31%, 8.12 %, and 2.68% accordingly referring to D80-B10-PE10, D75-B10-PE15, D85-B10-HE5, D80-B10-HE10 and D75-B10-HE15. All output power curves of tri-fuel blends are very similar to neat DF. It must be noticed that the higher the percentage of alcohol in the tri-fuel blends, the closer the output curve is to that of DF. The power loss due to a low calorific value POME is 39.72kg/KJ, that compensated by a higher presence of oxygen, which leads to a better combustion. Another reason for these occurrences is due low cetane number of PE and HE causes an increase of the ignition delay. Consequently, the engine brake power become lower, and so does the increase of premixed fuel combustion phase after the start of ignition (Campos-Fernández et al. 2012). By the other hand, the reduction is due to high density and high kinematic viscosity of POME, which provide proper atomization. Moreover, oxygen content of a tri-fuel blends created fuel-lean regions in the combustion chamber, which provided an advantage in terms of exhaust gas emissions. According to Buyukkaya (2010), viscosity is the best reasons to explain the reduction of brake power and torque, due to lower heating value under full load conditions.

However, when tri-fuel blends are compared to DF, at 100% engine load the brake power increased by 25.18%, 24.22%, 22.92%, 22.11%, 14.85% and 21.65%, while the brake torque also increased by 25.21%, 24.25%, 22.96%, 22.13%, 14.88% and 21.68%, respectively referring to the both brake power and brake torque of D85-B10-PE5, D80-B10-PE10, D75-B10-PE15, D85-B10-HE5 and D75-B10-HE15. This is because the higher kinematic viscosity and density of tri-fuel blends have been which ensure high temperature and pressure as well as more air in-cylinder at the injection timing. Therefore, the presence of oxygen content molecules in long-chain alcohol will provide better combustion and increase brake power and torque consequently causing higher BTE. Other than that, the factor of lowering fuel consumption and improved BSFC resulted in increase in brake power. Increasing the proportion of pentanol in biodiesel blends, reduced the density and viscosity significantly. Therefore, the tri-fuel blends affected the increment of brake power and torque at high engine loads, thus increase mixture momentum and consequently the penetration depth in-cylinder. Finally, the brake power and torque with biodiesel when can increase considerably compared with DF by applying the turbo charger application to engine, in which according to Karabektas (2009) researched it in effect of turbocharger on rapeseed oil methyl ester.

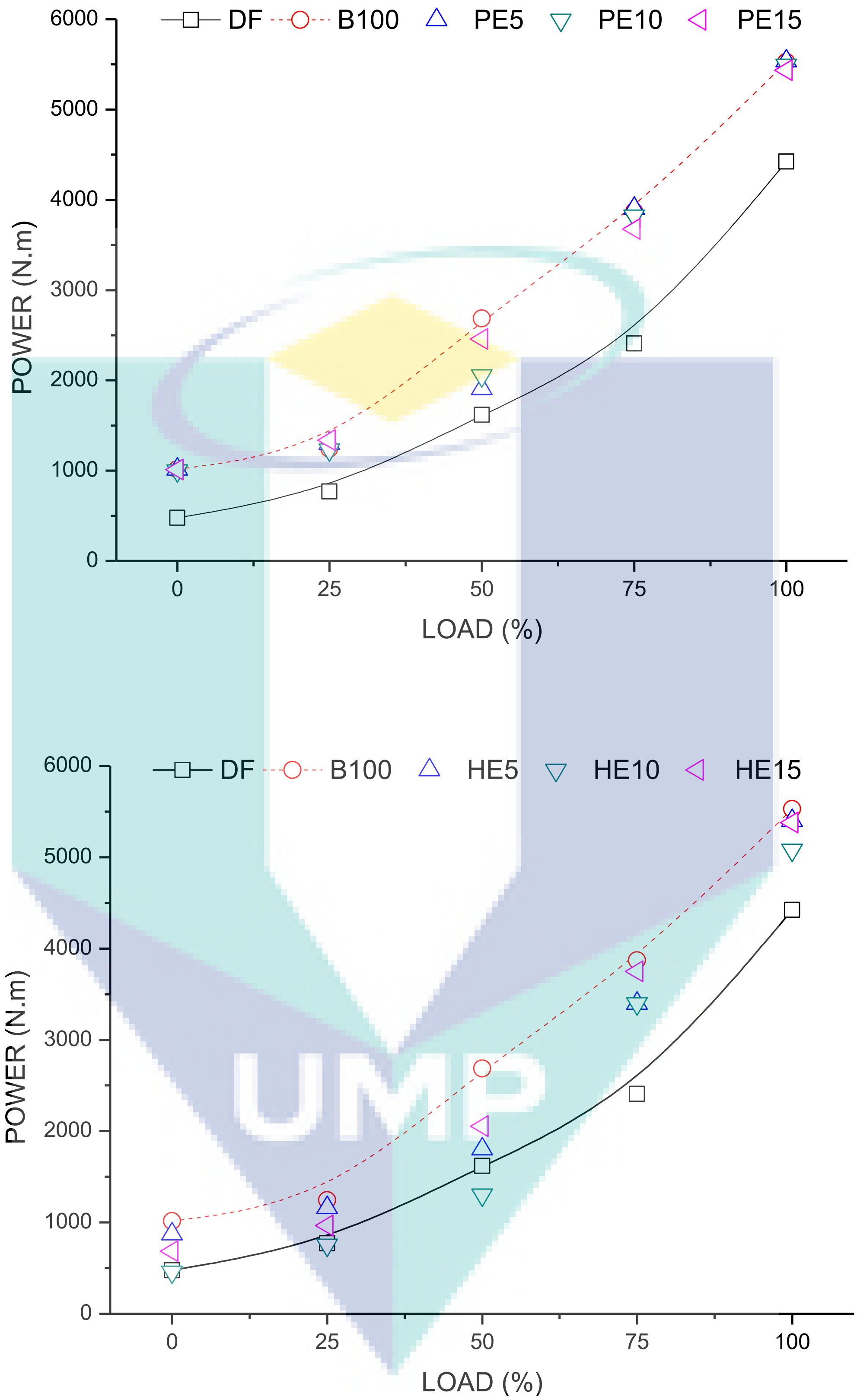


Figure 4.10 Variation brake power for PE and HE in various engine loads

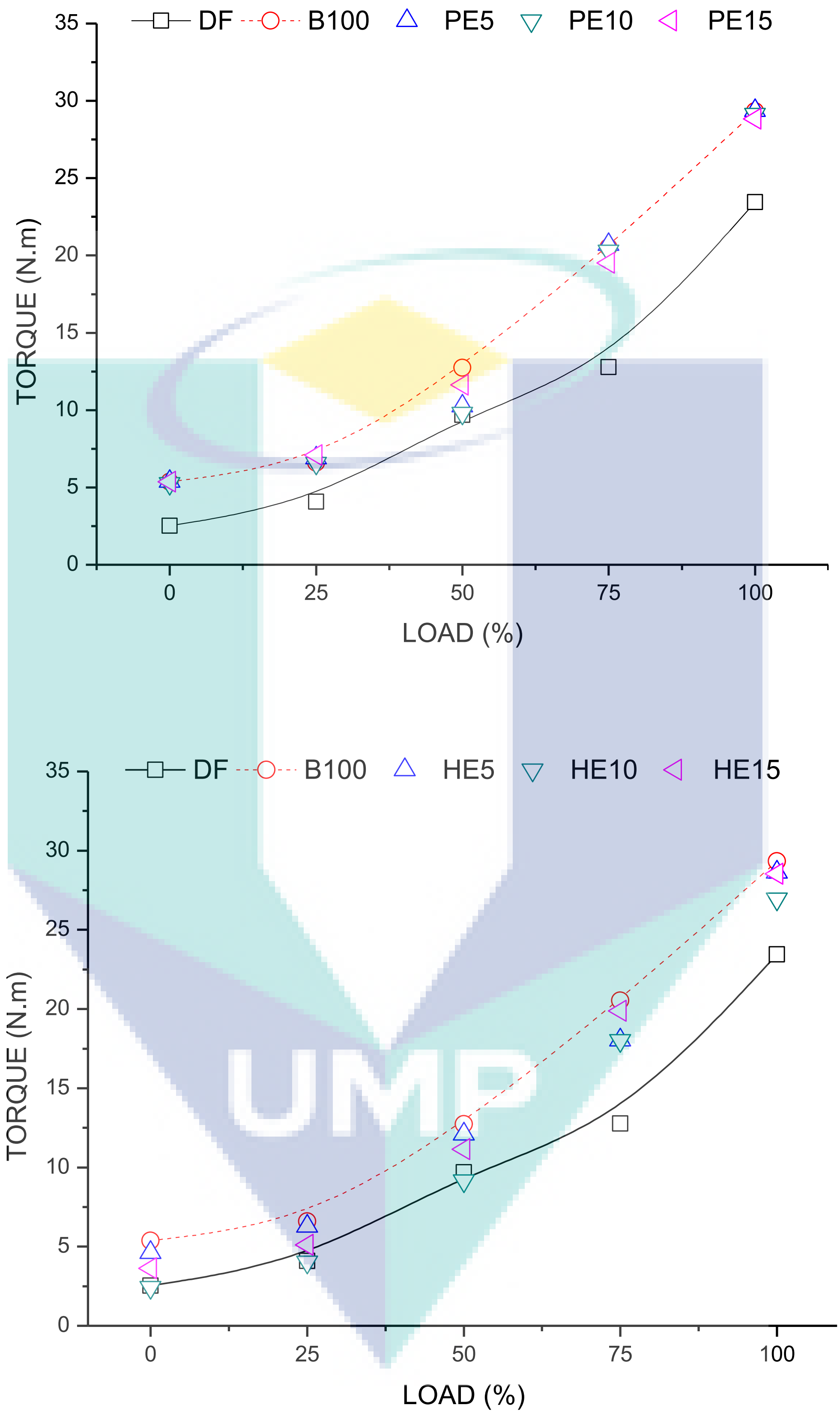


Figure 4.11 Variation brake torque for PE and HE in various engine loads

4.5.4 Exhaust emissions

This section of subchapter will discuss thoroughly on the second objective, which is to analyse the long-chain alcohol-biodiesel-diesel tri-fuel blends exhaust emissions. Another important test parameter in engine performance is the evaluation of gas emissions produced by fuel tests. After the engine has stabilized in working conditional, the used of QRO-401 gas analyser will measure exhaust emission, such as CO, CO2 and NO_x.

CO emissions are basically formed in rich air-fuel mixture region as a result of the inaccessibility of oxygen elements to oxidize the entire proportion of CO in the fuel. Figure 4.12 shows the formation of CO emission of fuel blends with respect to various engine loads at a constant engine speed of 1800 rpm. Overall, the formation of CO emission increases as engine load increases in both PE and HE fuel blends. The percentage of CO increased is due to the rising temperature in the combustion chamber, the physical and chemical properties of a tri-fuel blends, the air-fuel ratio, the shortage of oxygen especially at high engine load, and the lower time available for complete combustion.

In comparison to DF, the formation CO emission was reduced by 17.60%, 18.20%, 25.86%, 28.21%, 6.45% and 8.02% for D85-B10-PE5, D80-B10-PE10, D75-B10-PE15, D85-B10-HE5, D80-B10-HE10 and D75-B10-HE15 at 25% engine load. The highest reduction was 25.86% for D75-B10-PE15 and 28.21% for D85-B10-HE5. CO emissions expresses the lost chemical energy, is an important parameter through the exhaust gases. In addition, CO emission in the exhaust can identify the incomplete combustion because of the inadequate amount of oxygen in the combustion chamber. Biodiesel fuel and alcohols include much more oxygen in the structure than DF. Another reason for reduction the CO emission is cetane number of tri-fuel, due to the high cetane number can ensure a near complete combustion in the combustion chamber. The reduction of CO emissions caused by an increase in the amount of oxygen content in tri-fuel blends leads to complete combustion, and POME occupied a low carbon atom. Moreover, the increase in volume concentration of long-chain alcohol has led to decreased in CO emissions. Therefore, this effect helps in blending process and reduces the formation of CO emission. The tri-fuel blend of D75-B10-PE15 with a high ratio PE contents improve air-fuel mixing process, particularly in fuel-rich region of the combustion chamber by providing oxygen elements. The same trend was found by Yesilyurt et al. (2018) CO emission of B20P5 and B20P10 (70% DF + 20% biodiesel + 10% pentanol) were decreased by 24.80% and 32.40% compared to DF. This is due to pentanol added fuels showed better results owing to the oxygen content.

Conversely, at high engine loads, the formation of CO increased by 1.39%, 15.86%, 16.96%, 25.60%, 19.92% as well as 4.49% for D85-B10-PE5, D80-B10-PE10, D75-B10-PE15, D85-B10-HE5, D80-B10-HE10 and D75-B10-HE15 compared to B100. The reason of increment of CO formation at 100% engine load was due to the lower cetane number of tri-fuel blends. As such, the lower cetane number of fuel blends will prolong premixed combustion stage, resulting in less oxidation of carbon and oxygen that rise formation of CO. Besides, the highest deficiency of oxygen content causes incomplete combustion. Therefore, the cooling effect of long-chain alcohol, that is due to higher low heating value will be oxidized and converted CO to CO_2. The different CO emissions level is influenced by additive fuel, due to thermo-physical properties fuel blends added with additive fuel.

4.5.4.1 Carbon Monoxide emission

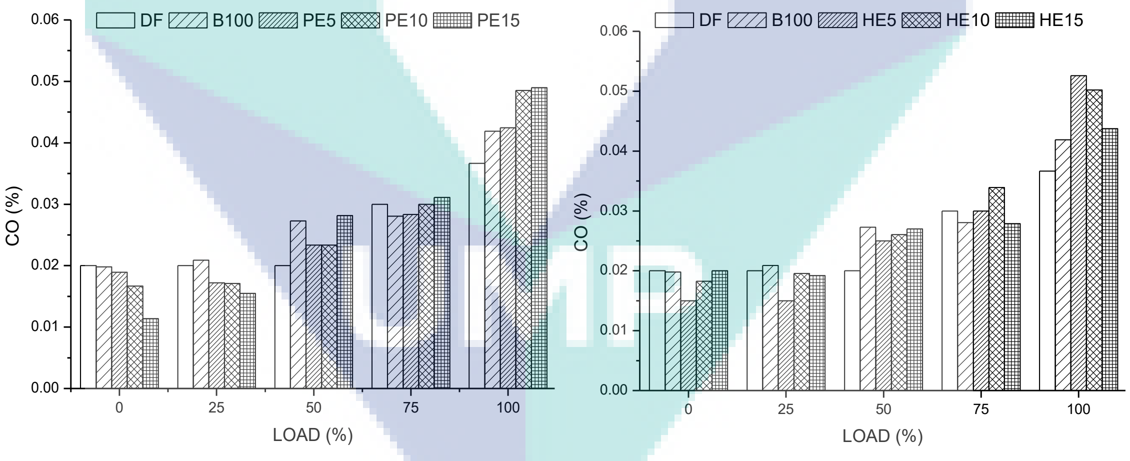
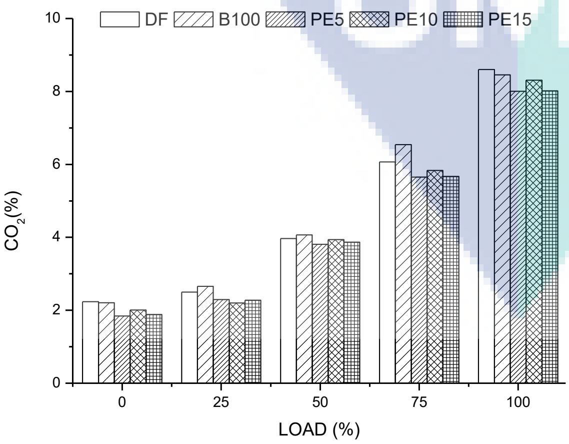


Figure 4.12 The formation of CO emissions versus engine loads for tri-fuel blends

4.5.4.2 Carbon Dioxide emission

When adequate oxygen elements are accessible, hydroxyl radical OH is one of the principal oxidizing agents that converts CO into CO_2. Figure 4.13 illustrated the formation of CO_2 emissions versus engine loads for fuel blends at a constant engine speed 1800 rpm. Observation from the figure found that CO_2 will continuously increase as increments of engine loads. Compared to both types of long-chain alcohol PE and HE, the formation CO_2 emissions of PE show higher than HE. The increments of CO_2 emission are due to increasing oxygen and hydrogen molecules in tri-fuel blends structure, and CO_2 emission that was reduced. Thus, in every engine load, the results show that there are no noticeable differences in CO_2 emissions measured compared to DF. The highest reduction occurred at 100% engine load by 6.92%, 3.42%, 6.79%, 8.02%, 13.23% and 11.36% for D85-B10-PE5, D80-B10-PE10, D75-B10-PE15, D85-B10-HE5, D80-B10-HE10 and D75-B10-HE15 compared to DF. In addition, increasing oxygen and hydrogen molecules in tri-fuel structures will result in the reduction of CO_2 emission, due to the chemical structure of long-chain alcohol having low carbon atoms per unit volume, especially for PE. Other than that, low operating temperature occur in diesel engines due to the high latent heat of vaporization long-chain alcohol. Since the CO_2 emission, highly influence the greenhouse effect and global warming, it is necessary to ensure that the CO_2 emission is decreased from the engine. As stated by Abdullah et al. (2019), 2-ethyl-1-hexanol blended with biodiesel and DF, the 2-ethy;l-i-hexanol is one of the oxygenated agents comprising a higher amount of oxygen atom in tri-fuel blends that gets formation of CO_2 emissions.



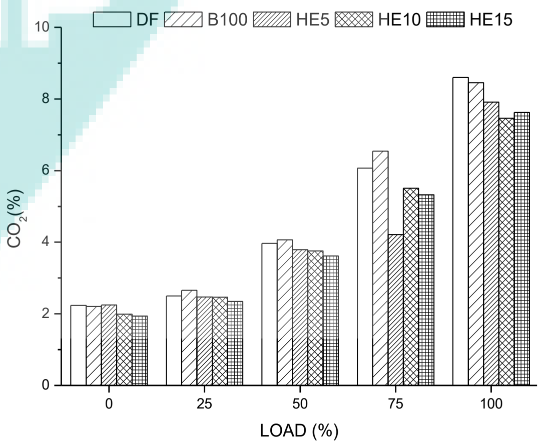


Figure 4.13 The formation of CO_2 emissions versus engine loads for tri-fuel blends

The variation of NO_x emission for all tri-fuel blends with respect to engine loads and at 1800 rpm engine speed are shown in Figure 4.14. The formation of NO_x emission happens at high combustion temperature, which occurs during complete combustion, mostly at high engine load. In general observation, NO_x emissions increase as the engine load increases. The increment is expected due to the in-cylinder gas temperature increases with an increase in engine load, leading to higher NO_x emissions. Referring to the figure, it can be seen that tri-fuel blends show no noticeable difference at low engine load. Nevertheless, the NO_x emissions slightly increase as observed for tri-fuel blends when engine load increased. Conversely, the higher percentage of long-chain alcohol leads to lower NO_x emissions at every increase's engine load.

At low range of engine load, NO_x emissions significantly reduced by 4.85%, 0.91%, 2.12%, 1.03%, 3.83% and 5.91%, respectively for D85-B10-PE5, D80-B10-PE10, D75-B10-PE15, D85-B10-HE5, D80-B10-HE10 and D75-B10-HE15 compared to DF. A small reduction in the formation of NO_x emission has been affected by the addition of long-chain alcohol, PE and HE content due to the cooling effect. This is caused by higher heat vaporization than DF, which gives lowering temperature effect, thus helps to lower in-cylinder temperature.

In addition, at high range engine load the reduction of NO_x emissions was significantly reduced by 12.75%, 10.57%, 20.65%, 15.82%, 19.36%, as well as 25.33% D85-B10-PE5, D80-B10-PE10, D75-B10-PE15, D85-B10-HE5, D80-B10-HE10 and D75-B10-HE15 compared to DF. As noted, the highest reduction occurs in the higher volume concentration of long-chain alcohol, which are 20.65% and 25.33% for D75-B10-PE15 including D75-B10-HE15. Therefore, the reduction of NO_x is important for achieving the objective and is the most harmful emission caused by diesel engines.

However, in every increasing step of engine load, the formation of NO_x emissions increases. This is due the lower cetane number, low kinematic viscosity and low density of long-chain alcohol, resulting in longer ignition delay and more fuel accumulated, thereby increasing the amount of fuel in premixed combustion. Thus, the post-combustion temperature increase, leading to higher NO_x emissions. As such, the oxygen content that contained n-pentanol might assist NO_x formation as reported by Wei et al. (2014) on effect of n-pentanol addition on the combustion, performance and emission characteristics.

4.5.4.3 Nitrogen Oxide emission

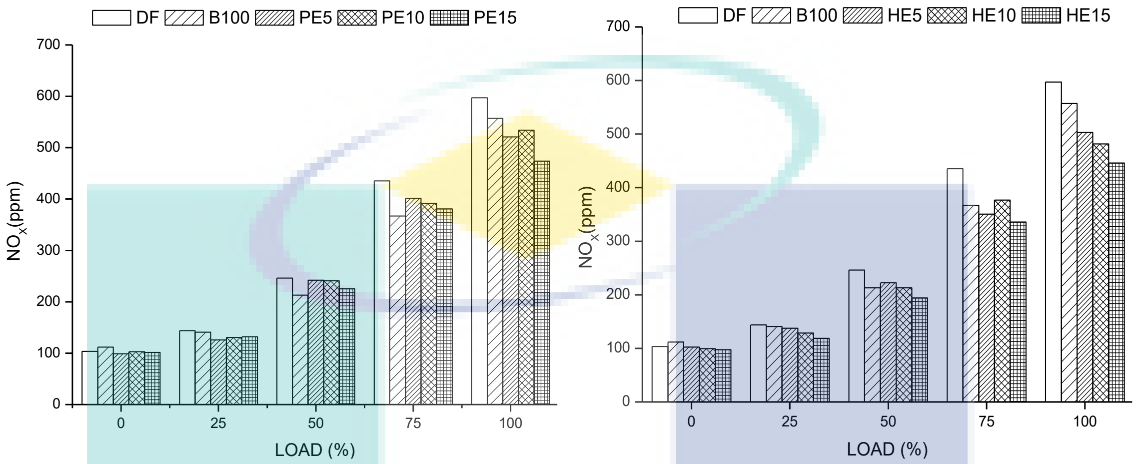


Figure 4.14 The formation of NO_x emissions versus engine loads for tri-fuel blends

4.6 Analysis the optimum blend ratio (Response Surface Methodology)

The Design Expert 7.00 software is used to operate and fit experimental readings into second order polynomial equations. Based on the analysis of the variables (ANOVA), the principle model analysis is implemented and provides numerical information for the p-value. As such, the selected significant, and models chosen must have a p-value less than 0.05. The ANOVA for different response parameter, such as BSFC and BTE for long-chain alcohol-biodiesel-diesel tri-fuel blends are shown in Table 4.3. Furthermore, various responses have been recorded to evaluate the suitability of selected models. The p-value that is less than 0.001 indicated that a significant model terms and reference limit have been set at 0.05. By using the regression coefficient, a second order polynomial model was developed in terms of coded factors. The quadratic model for the response was also developed in terms of actual and coded factors by using quadratic equations. In which the input parameter is engine loads (A) and percentage of long-chain alcohol in fuel mixture (B).

Table 4.3 Analysis of variables for responses (p-value)

	PE		HE	
Sources	BSFC (kg/kW.h)	BTE (%)	BSFC (kg/kW.h)	BTE (%)
Model	<0.0001	<0.0001	0.0006	0.0003
A	<0.0001	<0.0001	<0.0001	<0.0001
B	0.6571	0.8679	0.3680	0.3202
AB	0.5918	0.8300	0.2410	0.0910
A^2	0.0026	0.6089	0.1072	0.8057
B^2	0.8089	0.9747	0.0228	0.0321

Equation 4.1 - 4.4 interpreted the full second order polynomial function equation that contained all input variables. BSFC and BTE are the response of tri-fuel blends that used different type of long-chain alcohol, such as pentanol and hexanol. (A) is engine load, while (B) is the percentage of long-chain alcohol in fuel mixture. Factor A and B are referred as the main effects, while AB are the interaction effects. Equation 4.1 and Equation 4.2 was interpreted PE-biodiesel-diesel tri-fuel blends for BSFC and BTE, while Equation 4.3 and Equation 4.4 was interpreted HE-biodiesel-diesel tri-fuel for BSFC and BTE respectively.

$$BSFC = +308.20 - 181.96(A) + 5.43(B) - 9.30(AB) + 95.01(A^2) + 5.10(B^2) \tag{4.1}$$

$$BTE = +0.27 + 0.12(A) + 0.00146(B) - 0.00267(AB) - 0.00883\ (A^2) - 0.00048(B^2) \tag{4.2}$$

$$BSFC = +499.75 - 295.02(A) + 33.09(B) - 61.99(AB) + 121.92(A^2) - 165.72(B^2) \tag{4.3}$$

$$BTE = +0.20 + 0.12(A) - 0.014(B) + 0.034(AB) + 0.00634(A^2) + 0.056(B^2) \tag{4.4}$$

4.6.1 Evaluation of the model

After regression coefficients are obtained, the predicted response could be easily calculated using model equation. In order to validate the developed model, fitting test, data regression, significance analysis and individual model coefficient are presented in Table 4.4. The quality of the fitted polynomial function is expressed by the determination of the coefficient (R^2), which represents the proportion variability of the response as a result of the input variables. Nevertheless, the number of model variables increases, while the determination of coefficient R^2 also increases. Therefore, RSM recommends to use adjusted R^2, which decreases if unnecessary terms are added to the model. In this research, R^2 and adjusted R^2 were found to be close to each other, indicating a low chance for none significant term to be included in the model. In addition, lower value of coefficient of variation (CV) can be observed, suggesting a better precision and reliability of the experiments.

Table 4.4 Model evaluation

	PE		HE	
Sources	BSFC (g/kW.h)	BTE (%)	BSFC (g/kW.h)	BTE (%)
Mean	359.10	0.26	450.23	0.24
Std. Deviation	37.41	0.027	110.41	0.041
CV	10.42	10.33	24.52	16.79
Model degree	Quadratic	Quadratic	Quadratic	Quadratic
R^2	0.9559	0.9400	0.8812	0.9008
Adjusted R^2	0.9314	0.9067	0.8151	0.8457
Predicted R^2	0.8627	0.8450	0.5313	0.7270

4.6.2 Effect of fuel blends type and engine loads

Figure 4.16 and Figure 4.18 shows the contour and three-dimensional (3D) surface plot the effect of PE percentages against engine loads on BSFC and BTE. In more specific, lower limit and upper limit for BSFC were 211.586 g/kW.h and 649.626 g/kW.h, while the lower limit and upper limit for BTE were 0.1305% and 0.3849% as shown in Table 4.5. After analysed by RSM, the best selected blend ratio of predicted value was 220.794 g/kW.h and 0.3744% for BSFC and BTE of pentanol-biodiesel-diesel tri-fuel blends as shown in the figure. The actual value for BTE is 0.26%, 0.262% and 0.262%, while for predicted values is 0.26%, 0.262% and 0.262%, for D85-B10-PE5, D80-B10-PE10 and D75-B10-PE15 respectively as shown in Table 4.6. More so, the difference between actual value and predicted BTE has no change in the graph profiles for all response parameters. Thus, it can be concluded that RSM D85-B10-PE5, D80-B10-PE10 and D75-B10-PE15 modelling buildings successfully meet the model demands. Hence, the model developed in predicted value is in good agreement and RSM models for BSFC is accepted. The higher BTE found in predicted values is because of the increased oxygen content in tri-fuel blends, as volume concentration of alcohol increases. Moreover, the actual value of BSFC in average are 355.374 g/kW.h, 355.702 g/kW.h and 366.236 g/kW.h for D85-B10-PE5, D80-B10-PE10 and D75-B10-PE15, accordingly. The predicted values are found in the RSM analysis of BSFC, accurate and precise to actual value of 355.374 g/kW.h, 355.702 g/kW.h and 366.234 g/kW.h for D85-B10-PE5, D80-B10-PE10 and D75-B10-PE15, respectively as shown in Table 4.7. The percentage errors between actual value and predicted value does not have a significant effect on BSFC, and the differences were slightly lower in predicted value by 0.0005% in average compared to the actual value. Therefore, BSFC of pentanol-biodiesel-diesel trifuel blends can be used in diesel engines without any modification, due to the reduction of BSFC in performance. The reduction BSFC is due to lower density and calorific value of long-chain alcohol that have increased the injected fuel blends.

While Figure 4.15 and Figure 4.17 indicated the interaction of effect HE percentage against engine loads on BSFC and BTE in contour as well as 3D surface plot. In more detail, the lower limit and upper limit for BSFC were 218.389 g/kW.h and 1096.05 g/kW.h, in which the lower limit and upper limit for BTE were 0.0738% as well as 0.3727%. After being analysed by RSM, the best solution was 170.566 g/kW.h and 0.3819% for BSFC and BTE of hexanol-biodiesel-diesel tri-fuel blends as shown on figure. Observation from the graph shows that, BSFC of hexanol-biodiesel-diesel tri-fuel blends have the same results with pentanol. The actual value of BSFC in total average is 361.898 g/kW.h, 560.71 g/kW.h and 428.09 g/kW.h accordingly to D85-B10-HE5, D80-B10-HE10 and D75-B10-HE15. The predicted value is found in the RSM analysis of the BSFC, that it is accurately and precisely to actual value of 361.898 g/kW.h, 560.708 g/kW.h and 428.086 g/kW.h for D85-B10-HE5, D80-B10-HE10 and D75-B10-HE15. In addition, the actual value of BTE are 0.274%, 0.2048% and 0.246%, while for predicted value are 0.276%, 0.2026% and 0.2462% for D85-B10-HE5, D80-B10-HE10 and D75-B10-HE15 respectively. Overall observation, shows that the predicted value is lower by 0.0004% and 0.0877% than actual value on average of both responses (BSFC and BTE).

This result can be interpreted that the RSM model is accepted for hexanol-biodiesel-diesel tri-fuel blends. Finally, the improvement of BTE is due to the presence of oxygen molecules with the addition of alcohol, and improved combustion, especially diffusion combustion that has been improved and increased efficiency.

Table 4.5 Upper and lower limit of BSFC and BTE for PE and HE

	PE		HE	
Limit	BSFC (g/kW.h)	BTE (%)	BSFC (g/kW.h)	BTE (%)
Upper	649.626	0.3849	1096.05	0.3727
Lower	211.586	0.1305	218.389	0.0738

Table 4.6 Actual and predicted value for BTE

	PE5	**PE10**	**PE15**	**HE5**	**HE10**	**HE15**
Actual	0.26	0.262	0.262	0.274	0.2048	0.2462
Predicted	0.26	0.262	0.262	0.276	0.2026	0.2462

Table 4.7 Actual and predicted value for BSFC

	PE5	**PE10**	**PE15**	**HE5**	**HE10**	**HE15**
Actual	355.374	355.702	366.236	361.868	560.71	428.09
Predicted	355.374	355.702	366.234	361.898	560.708	428.086

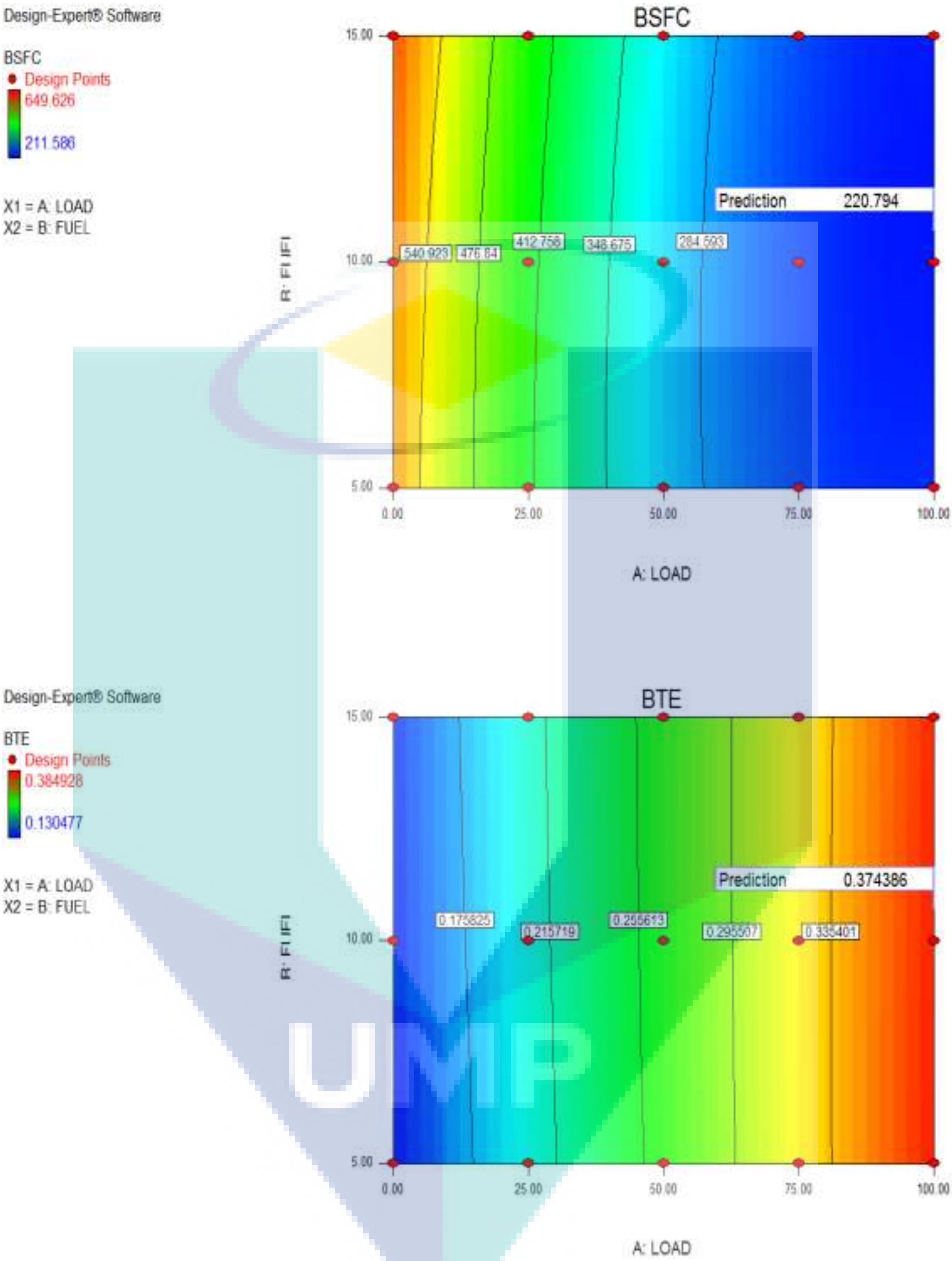


Figure 4.15 Contour plot of effect pentanol percentage and engine loads on BSFC and BTE

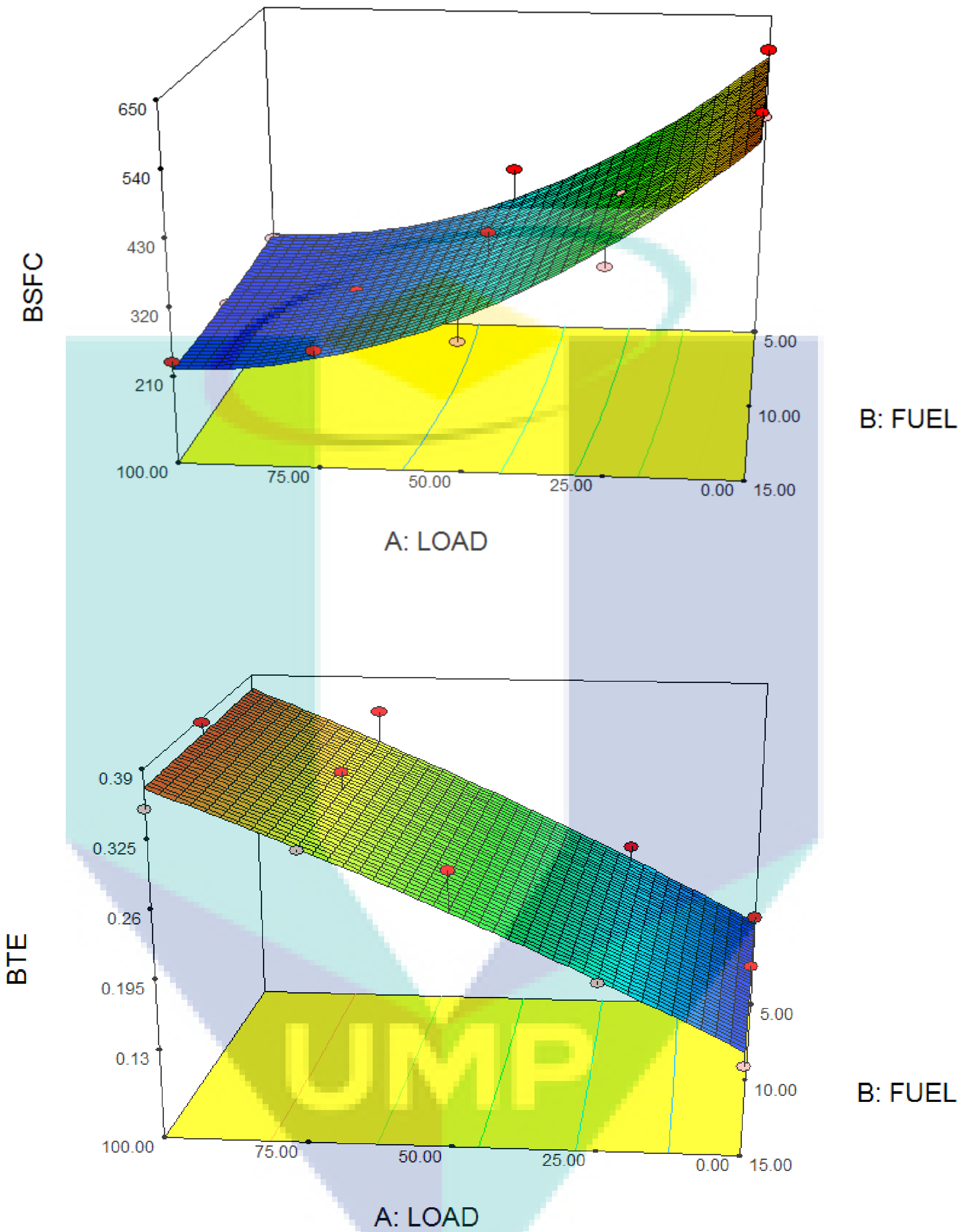


Figure 4.16 3D surface plot of effect pentanol percentage and engine loads on BSFC and BTE

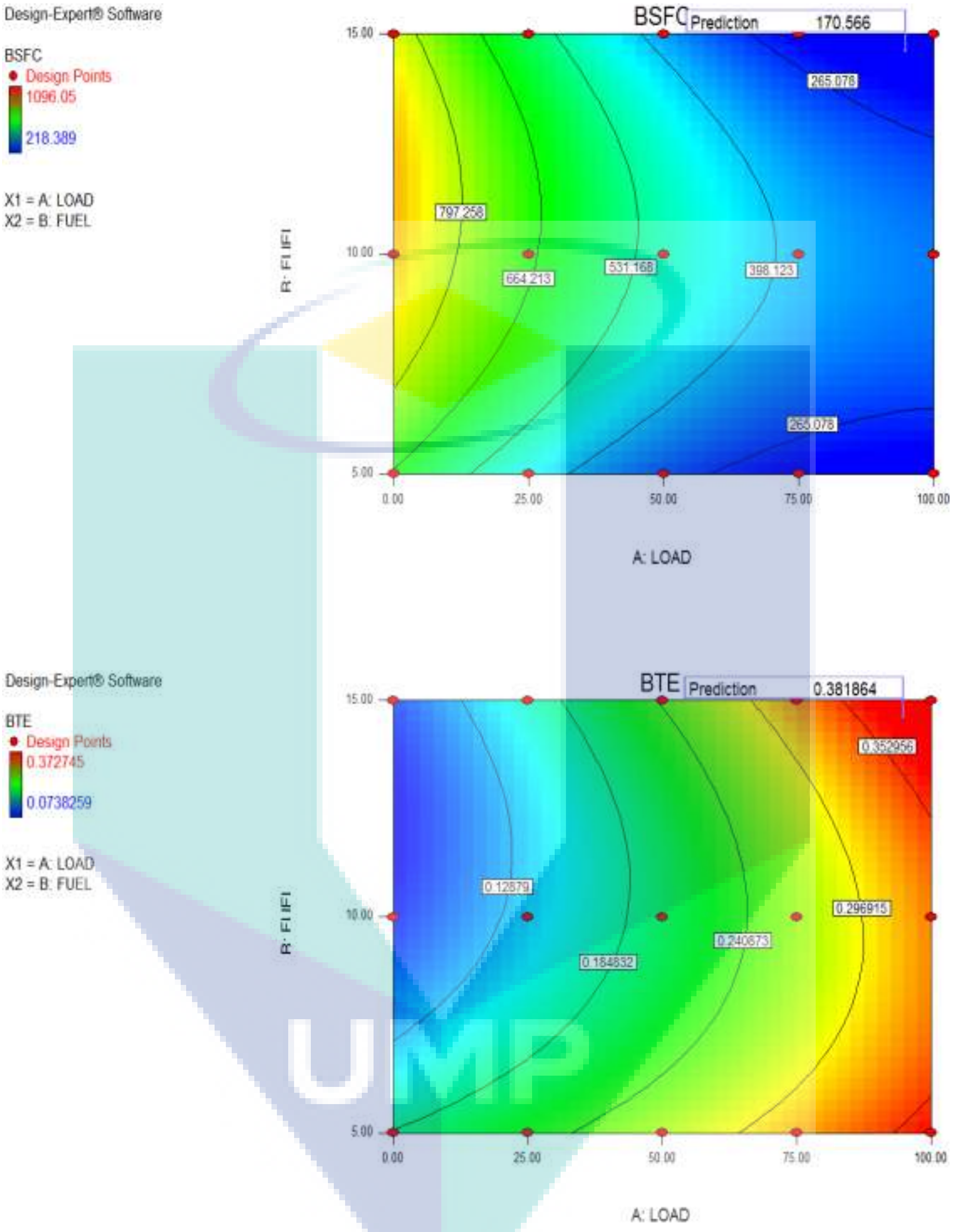


Figure 4.17 Contour plot of effect hexanol percentage and engine loads on BSFC and BTE

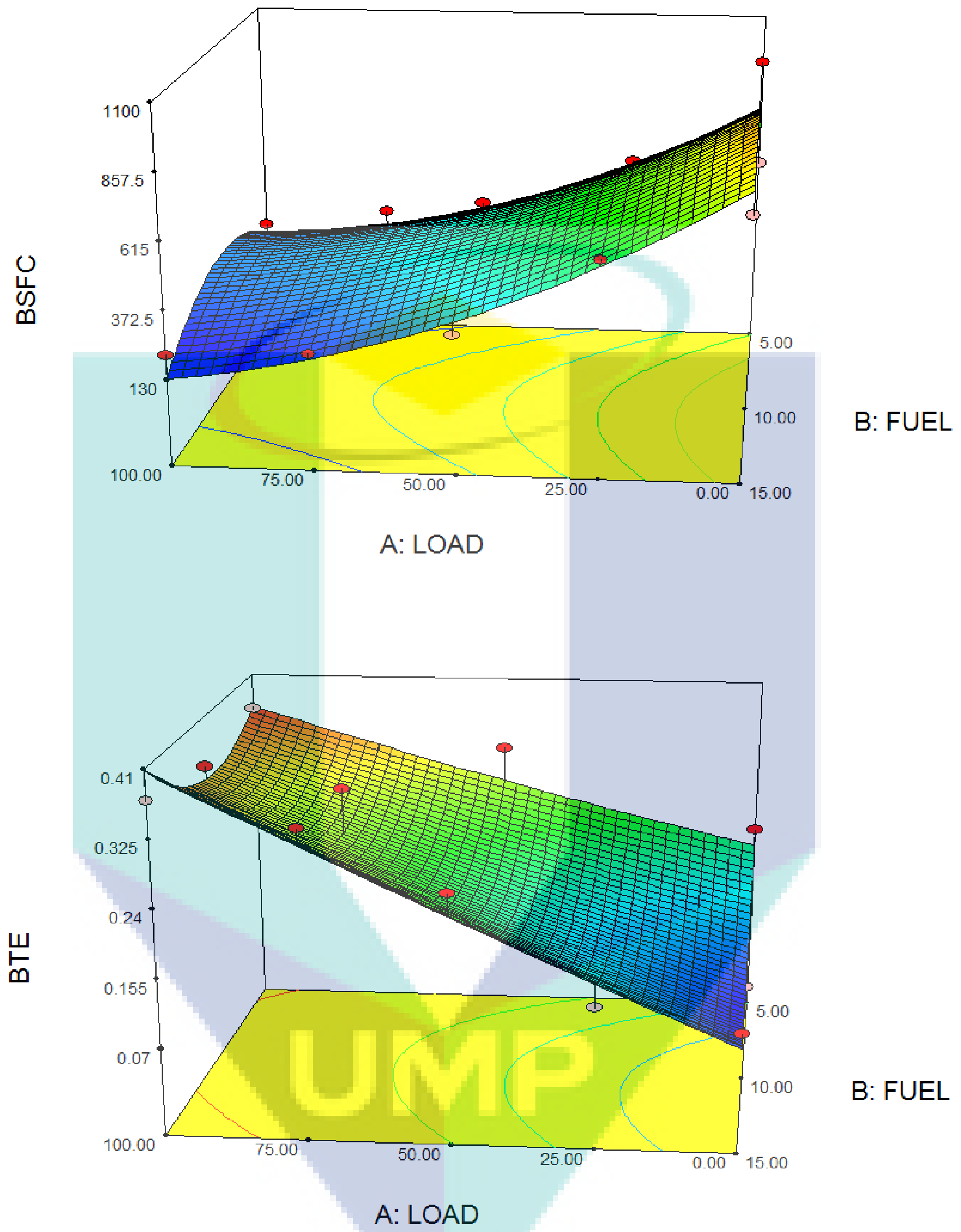


Figure 4.18 3D surface plot of effect hexanol percentage and engine loads on BSFC and BTE

4.6.3 Validation of the optimum blend ratio results

In this research, the Design Expert 7.0 the software was successfully analysed and the optimum blend ratio of factors, as well as optimum of the long-chain alcohol-biodiesel-diesel tri-fuel blends was discovered. After a set of each factor (engine loads and type of fuel blends) and responses (BSFC and BTE) were analysed, it was found that the optimization methodology able to indicated the selected optimum blend ratio. Also, in terms of parameters of RSM, the criteria for optimization engine loads and types of fuel blends were set as in range. While the optimization requirements for BSFC and BTE was set as minimum and maximum respectively. The input of engine loads is 0%, 25%, 50%, 75% and 100%, while for types of fuels blends are D85-B10-PE5, D80-B10-PE10, D75-B10-PE15, D85-B10-HE5, D80-B10-HE10 and D75-B10-HE15. The actual value, predicted value, and percentage errors of fuel blends, engine loads, BSFC, BTE was measured and calculated in Table 4.8. As such, the highest desirability-based approach of different factor was obtained for best solution. The highest desirability for PE/HE-biodiesel-diesel tri-fuel blends were 0.969 and 1.000 respectively. Among the fuel blends, D85-B10-PE5, D80-B10-PE10, D75-B10-PE15, D85-B10-HE5, D80-B10-HE10 and D75-B10-HE15, the selection of predicted value of fuel blends were D80-B10-PE10 for PE and D75-B10-HE15 for HE. In PE-biodiesel-diesel tri-fuel blends have predicted value selected 100%, and D80-B10-PE10.71, for engine load and type of fuel blends respectively, with percentage errors were none for engine load and 7.1% error for type of fuel blends. While for HE-biodiesel-diesel tri-fuel blends, the predicted value selected 94.80% and HE14.63, the percentage errors were 5.2% and 2.47% for engine load and type of fuel blends respectively. In addition, the validation results for BSFC and BTE for PE have percentage errors by 5.30% and 2.73% respectively. BSFC and BTE percentage errors for HE was 21.80% and 2.44% respectively as well. Overall best selected optimum blend ratio was closed to actual value for PE is 100% and D80-B10-PE10, while for HE is 100% and D75-B10-HE15 respectively. Therefore, the optimum blend ratio results from actual to predicted value that was developed from RSM were quite accurate as the percentage of error in good prediction. However, the BSFC in hexanol tri-fuel blends show the highest error by 21.80% due to the D80-B10-HE10, which showed a fluctuation results from 0% engine load to 100% engine load in BSFC graph. This is because the D80-B10-HE10 had quenching effect and lower in-cylinder temperature, since the calorific value of D80-B10-HE10 is 44.49MJ/kg.

Table 4.8 Table of optimum blend ratio

	PENTANOL			HEXANOL		
Parameter	Actual	Predicted	Error	Actual	Predicted	Error
Load	100	100	0	100	94.80	5.2%
Fuel	10.00	10.71	7.1%	15.00	14.63	2.47%
BSFC	211.586	222.794	5.30%	218.389	170.566	21.80%
BTE	0.3849	0.3744	2.73%	0.3728	0.3819	2.44%

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion of Study

The long-chain alcohol, PE and HE are promising alternative fuel additive, which shows a remarkable improvement in stability and thermo-physical properties, combustion characteristics, engine performances as well as exhaust emissions when blended with biodiesel and diesel to become tri-fuel blends. Hence, the addition of additive fuel can be used as a tri-fuel blends without any engine modification. Based on this, a long-chain alcohol-biodiesel-diesel tri-fuel blends are recognized as a new formulation alternative fuels that forming potential to substitute DF usage as a based fuel. In view of the results and discussions of the present study, the following points below emerged from the present analysis:

5.1.1 Objective 1

a) The observation on stability behaviour shown did not have any sedimentation or phase separation for tri-fuel blends after 10 days of blending process due to the high miscibility between the mixtures.

b) The thermo-physical properties, such as calorific value, cetane number, density, dynamic viscosity and kinematic viscosity have shown an improvement in every test fuel, due to the presence of B100 and long-chain alcohols as additive fuels.

5.1.2 Objective 2

a) D80-B10-PE10, D75-B10-PE15, D85-B10-HE5, D80-B10-HE10 and D75-B10-HE15 slightly reduced by 2.91%, 0.66%, 0.54%, 5.67% and 1.66% compared to DF at engine load 100%, the reduction is due to the high temperature at peak pressure in-cylinder pressure may weaken the cooling effect.

b) D75-B10-HE15 by 31.98% on 100% engine load compared with DF. The HRR increases as engine load increases. The maximum increment peak of HRR is This is due to the influence of the high temperature rise and high cylinder pressure for a better air-fuel mixture, which is also causing quenching effect.

c) Engine performance efficiency has BTE that shows the maximum improvement occurs at 100% engine load for DF, B100, D85-B10-PE5, D80-B10-PE10, D75-B10-PE15, D85-B10-PE5, D80-B10-PE10 and D75-B10-PE15 with 0.3125%, 0.3728%, 0.3663%, 0.3849%, 0.3540%, 0.3636%, 0.3480%, and 0.3727% respectively. The improvement is due to long-chain alcohols which consists of high oxygen content leading to a better atomization.

d) The BSFC shows an improvement especially for tri-fuel blends D80-B10-PE10 and D75-B10-HE15 which saved 13.75% and 12.19% respectively of fuel consumption compared to DF at 100% engine load. The reduction is due to higher oxygen content that supplies high power during the combustion process, thus increasing the efficiency.

e) Both brake power and torque are slightly increased by 24.22%, 21.65 for power, 24.25% and 21.68% for torque, both accordance to D80-B10-PE10 and D75-B10-HE15 tri-fuel blends respectively occurring at 100% engine load, compared to DF. The increment is due to higher kinematic viscosity and high density of biodiesel that has been compensated with a diesel engine to ensure high temperatures and more pressure air in-cylinder injection timing.

f) The reduction of CO_2 and NO_x of D75-B10-PE15 by 6.79%, and 20.65% compared to DF occurred at 100% engine load due to the enrichment oxygen content in long-chain alcohol volume concentration and better atomization process.

5.1.3 Objective 3

a) The optimum fuel blends for PE with DF was 10.71% ratio of 1-pentanol at engine load 100%.

b) The optimum fuel blends for HE with DF was 14.63% ratio of 2-ethyl-1-hexanol at engine load 94.80%.

From the summarising conclusion above, there is a proofing evidence that all objectives are achieved in this research. The new formulation long-chain alcohol-biodiesel-diesel tri-fuel blends D85-B10-PE5, D80-B10-PE10, D75-B10-PE15, D85-B10-HE5, D80-B10-HE10 and D75-B10-HE15 can be tested in diesel engines without any modification. The percentage of volume ratio for long-chain alcohol (PE and HE) are 5%, 10% and 15% each of long-chain alcohol, while constant volume ratio with 10% of B100 and 85%, 80% and 75% for DF respectively. The constant volume ratio for B100, is due to concentrate to performance, effect and efficiency of long-chain alcohol in diesel engine. In overall outcome, the stability behaviour shows a stable tri-fuel blends. In terms of thermo-physical properties, the advantages of each additive fuel play the role of their own strengths in tri-fuel blends to meet DF demands. Also, combustion characteristics, showing in-cylinder pressure and HRR have shortened the ignition delay due to the presence of biodiesel, thermo-physical properties in high kinematic viscosity and high density. The engine performance is greatly improved in terms of BSFC and BTE during running in diesel engines. Consequently, the fuel consumption is reduced due to the presence of oxygen content, leading to a better atomization, and thus increase efficiency. Last but least, exhaust emissions are reduced in CO_2 and NO_x compared to DF, especially at high engine load. Lastly, the optimum blend ratio was selected D80-B10-PE10 and D75-B10-HE15 the most predicted to the actual value also closed to the DF. Apparently, the addition of long-chain alcohol, PE and HE with biodiesel and diesel are shown to be a positive impact on combustion and performance in life of diesel engines.

5.2 Recommendation

5.2.1 Formulation new test fuel blends

A good alternative fuel must satisfy many requirements, such as sufficient lubricity, suitable vapour pressure, viscosity and safe handling characteristics. In this research, PE and HE long-chain alcohol is blended with POME and DF to become tri-fuel blends. Therefore, for the next studies, heptanol and octanol can be used as additive fuel due to rarely research conducted type of alcohols. Other than that, biodiesel that is currently in used is POME, future studies may include animal fat, waste cooking oil that is collected form restaurant, algae oil or etc. to avoid wastage.

5.2.2 Comparison experimental and simulation

As applied in this research, RSM simulation is used to find the optimum blend ratio between actual value and predicted value. In future studies, researchers can try to find other simulations to generate or build the best or selective response to be applied directly in the industry. Although, the constraints are carrying out experiment engine testing, such as uncontrolled parameter, humidity, working temperature and friction. Therefore, simulation results can be used to compare the experimental testing with expected results. Finally, tri-fuel blends can also be done with various type of engines.

5.2.3 New parameter and features of thermo-physical properties

New features and parameter have to more widely, such as lubricity, vapor pressure, viscosity and others features of thermo-physical properties. Other than that, the new apparatus must be added, such as temperature in the in-cylinder pressure was mounted to the combustion chamber. This is because the increments of temperature in in-cylinder pressure was affected to the engine performance and combustion characteristics efficiency. The apparatus needed is thermocouple, particulate matter measurement, oxygen content and others apparatus needed.

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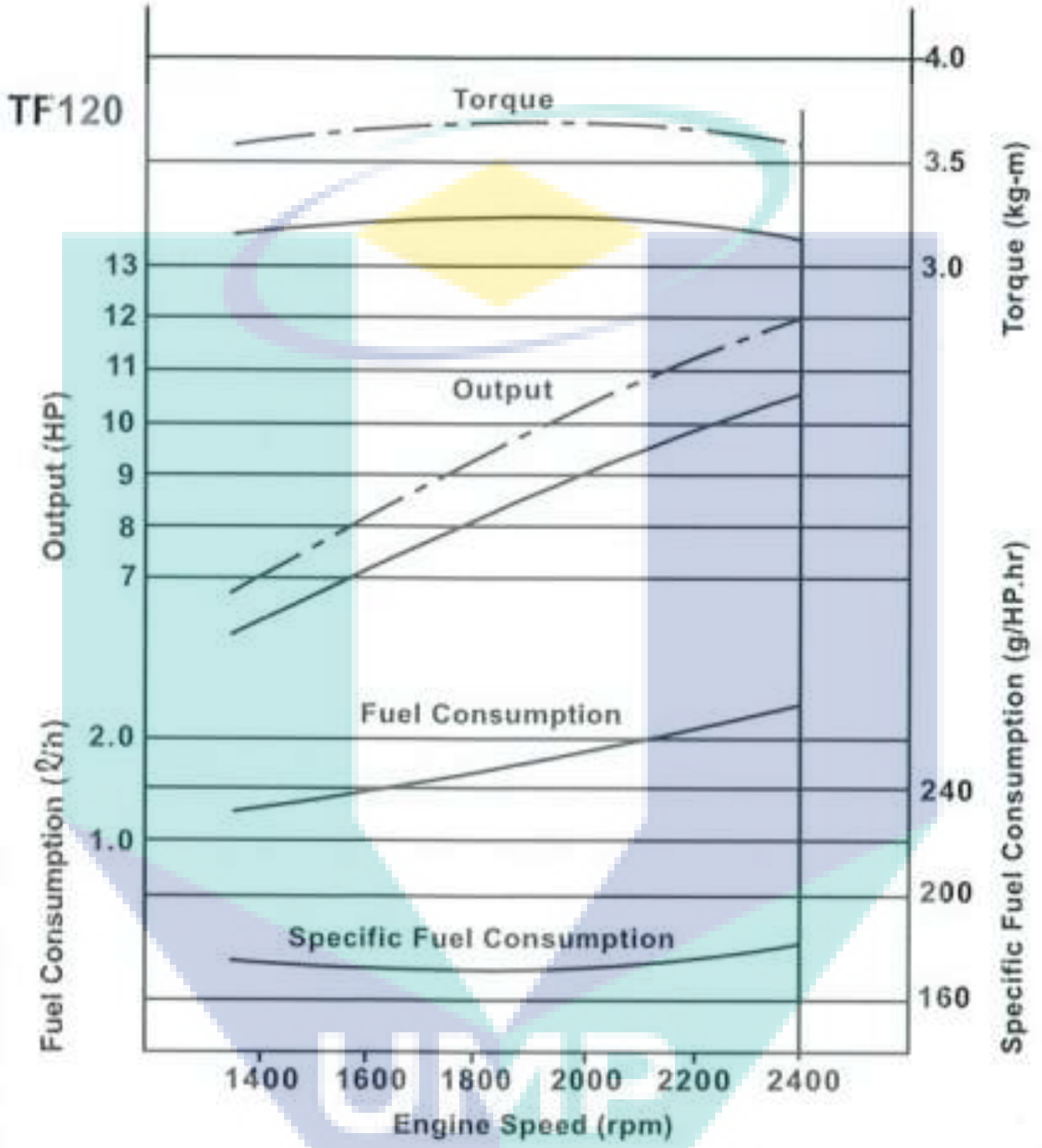
APPENDIX A
GAS ANALYSER SPECIFICATION

Target Subject	CO, HC, CO_2, O2, λ (Excess Air Ratio), AFR, NO_x			
Sensor Theory	CO, HC, CO_2: Non-Dispersive Infrared Analysis (NDIR) O2, NOx: Electrochemical Cell			
Analysis Range	CO	0.00 ~ 9.99%	HC	0 ~ 9999 ppm
Resolving Power		0.01%		1 ppm
Display		4-digit 7segment LED		4-digit 7segment LED
Analysis Range	CO_2	0.0 ~ 20.0%	O_2	0.00 ~ 25.00 %
Resolving Power		0.1%		0.01 %
Display		4-digit 7segment LED		4-digit 7segment LED
Analysis Range	λ	0 ~ 2.000	NO_x	0 ~ 5,000ppm
Resolving Power		0.001		1 ppm
Display		4-digit 7segment LED		4-digit 7segment LED
Repetition Rate	Lower than ±2% FS			
Response Time	Within 10 seconds (90% of the time)			
Preheat Time	Approx. 2~8 minutes			
Sample Requirement	4 ~ 6 L/min			
Voltage Use	AC110V or AC220V ±10%, 50/60Hz			
Power Consumption	Approx. 50W			
Temperature	0℃ ~ 40℃			
Size	285 (W) * 410 (D) * 155 (H) mm			
Weight	Approx. 4.5kg			

APPENDIX B
ENGINE PERFORMANCE



APPENDIX C
LIST OF PUBLICATIONS

A. International and National Journal

1. **Zuhaira Abdullah,** Hazrulzurina Suhaimi, Adam Abdullah, Mohd Firdaus Taufik, and Anes G. Mrwan, Effect of Pentanol-Diesel Fuel Blends on Thermo-Physical Prop1erties, Combustion Characteristics, Engine Performance and Emissions of a Diesel Engine, International Journal of Automotive and Mechanical Engineering, Volume 15, Issue 3, Pages 5435-5450.
2. Hazrulzurina Suhaimi, Abdullah Adam, Anes G. Mrwan, **Zuhaira Abdullah**, Mohd. Fahmi Othman, Mohd. Kamal Kamaruzzaman, Ftwi Yohaness Hagos, Analysis of Combustion Characteristics, Engine Performance and Emissions of Long-Chain Alcohol-Diesel Fuel Blends, Fuel, Volume 220, Pages 682-691.

B. International and National Conference Paper

1. **Zuhaira Abdullah**, Adam Abdullah, Hazrulzurina Suhaimi, and Mohd Akmal, Impact of Diesel-Biodiesel-Hexanol Tri-Fuel Blends on The Combustion and Exhaust Emissions Characteristics of a Diesel Engine, IOP Conference Series: Materials Science and Engineering, Volume 469.
2. A. Mrwan, A. Adam, H. Suhaimi, **Z. Abdullah,** and A. Adzmi, Blending long chain alcohol as a fuel additive with palm oil biodiesel and analysing the effects of blends on combustion, characteristics, performances and emissions of a diesel engine, AIP Conference Proceedings, Volume 2059, Issue 1.
3. H. Zurina, A. Adam, G. M. Anes, **Zuhaira Abdullah**, M. Fahmi, M. Kamal, and F. Y. Hagos, A comparative analysis on emissions of some next generation long-chain alcohol/diesel blends in a direct-injection diesel engine, AIP Conference Proceedings Volume 2059, Issue 1.