INVESTIGATION OF PARTICULATE MATTER AND COMBUSTION CHARACTERISTICS OF A DIESEL ENGINE FUELED WITH PALM OIL METHYL ESTER AND DIESEL BLENDS

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ABSTRACT

Diesel engines are attractive power units that are used widely in many fields and have become one of the larger contributors of total petroleum consumption. However, diesel engines are among the main contributors to emissions into the air, especially particulate matter (PM) and nitrogen oxides (NOx). PM is one of the major pollutants emitted by diesel engines and has adverse effects on human health. However, not many studies have been conducted on the PM concentration and PM morphological and size distribution on biodiesel fuel. Biodiesel, which produces less PM than diesel fuel, is preferred as an alternative source for diesel engines. Therefore, using palm oil methyl ester (POME) for diesel engines would be a more economical and sustainable solution. The objective of this research is to study the PM emissions characteristic from diesel engines fuelled with a diesel and POME blend. A transmission electron microscope (TEM) was used to determine the aggregate fractal prefactor, spherule, and aggregate size distribution. A comparison between diesel and the POME blend was made in terms of PM characterization, which involves PM mass concentration, its components soluble organic fraction (SOF) and dry soot (DS), and its influence on PM morphology such as spherule and aggregate correlation. Combustion characteristics such as in-cylinder pressure and rate of heat release of the engine as well as gaseous emissions were also observed at different operating engine loads. The results show that PM emissions of B100 are lower than those of diesel fuel owing to the oxygen content of POME. Observations of images on PM morphology showed a chainlike agglomeration, which is an extremely small non-uniform nanostructure. Simultaneously, the aggregate size distribution shifted to a smaller diameter as the blending ratio of POME in the fuel increased. The observation of in-cylinder pressure showed that the increment of pressure with the increasing POME blend as well as the increasing engine load is due to high cetane number for B100 that led to a shorten ignition delay. The engine brake thermal efficiency between the POME blend and mineral diesel was comparable. Furthermore, B100 fuels showed lower engine power at higher brake-specific fuel consumption compared to other tested fuels. In terms of gaseous emissions, increasing POME blends led to an increase in CO_2 and NOx while decreasing CO emission. Meanwhile, as the engine load increased, CO_2, NOx and CO also continued to increase. The effect of the POME blend on the PM-NOx trade-off observation showed that B100 simultaneously increased the NOx and decreased the PM emission. Both the wavelet analysis and coefficient of variation revealed that increasing the POME ratio provided a noticeable effect on increasing the engine cycle-to-cycle variations. It can be concluded that POME creates lower PM concentration while giving some negative feedback to NOx and resulting in smaller particle size. Moreover, the findings reveal that by having the wavelet analysis, one can predict the behavior of the PM emissions and subsequently further research helps to reduce them effectively and economically.

ABSTRAK

Enjin diesel merupakan unit kuasa yang digunakan secara meluas dalam banyak bidang dan menjadi salah satu penyumbang besar di dalam industri petroleum. Walau bagaimanapun, enjin diesel juga adalah antara penyumbang utama kepada pencemaran udara terutamanya bahan zarahan (PM) dan oksida nitrogen (NOx). PM adalah salah satu daripada punca pencemaran udara yang dihasilkan oleh enjin diesel dan mempunyai kesan yang buruk ke atas kesihatan manusia. Walaubagaimanapun, masih kurang penyelidikan tentang kepekatan PM dan morphologi dan juga saiz PM. Biodiesel adalah salah satu pilihan sumber alternatif untuk enjin diesel yang menghasilkan PM lebih rendah daripada bahan api diesel. Oleh itu, dengan menggunakan minyak sawit (POME), enjin diesel akan menjadi lebih ekonomi dan mampan. Objecktif kajian ini adalah untuk mengkaji pencemaran PM enjin diesel dengan menggunakan minyak diesel dan adunan POME. Perbandingan antara diesel dan adunan POME telah dibuat dari segi pencirian PM dimana kepekatan jisim PM, komponennya SOF dan DS dan pengaruhnya terhadap PM morfologi seperti diameter bulatan kecil dan mengumpulkan korelasi boleh ditentukan. Di samping itu, agregat prefactor fraktal, bulatan kecil dan taburan saiz agregat juga dibincangkan secara terperinci. Di samping itu, ciri-ciri pembakaran seperti tekanan di dalam silinder dan kadar pembebasan haba enjin serta pelepasan gas juga telah diperhatikan pada enjin dengan operasi beban yang berbeza. Keputusan menunjukkan pelepasan PM B100 adalah lebih rendah daripada bahan api diesel kerana kandungan oksigen yang terdapat di dalam POME. Pemerhatian ke atas imej PM morfologi menunjukkan bahawa ia berbentuk seperti rantai di mana struktur sangat kecil dan tidak seragam. Pada masa yang sama, taburan saiz agregat telah beralih kepada diameter yang lebih kecil diesebabkan oleh nisbah adunan POME dalam bahan api meningkat. Pemerhatian tekanan di dalam silinder menunjukkan bahawa kenaikan tekanan dengan peratusan adunan POME serta beban enjin yang semakin meningkat disebabkan oleh peningkatan nombor cetane untuk B100 yang menyebabkan pencucuhan yang singkat. Kecekapan brek haba enjin adalah setanding dengan adunan POME dan juga minyak diesel. Tambahan pula, bahan api B100 menunjukkan kuasa enjin yang rendah ketika peningkatan pada brek penggunaan bahan api berbanding bahan api yang lain. Dari segi pencemaran gas, peningkatan adunan POME menyebabkan kepada peningkatan dalam pencemaran CO_2 dan NOx manakala mengurangkan pencemaran CO. Selain itu, peningkatan beban enjin menyebabkan CO_2, NOx dan CO juga semakin meningkat. Kesan adunan POME di PM-NOx menunjukkan B100 meningkatkan NO_x dan mengurangkan pelepasan PM. Kedua-dua analisis wavelet dan pekali variasi menunjukan bahawa peningkatan nisbah POME akan memberi kesan yang ketara terhadap peningkatan variasi kitaran ke kitaran. Kesimpulanya POME memberikan kepekatan PM yang lebih rendah tetapi memberikan beberapa kesan negatif kepada NOx dan juga menghasilkan saiz zarah yang lebih kecil. Di samping itu, dengan adanya analisis wavelet, seseorang dapat menjakakan perubahan pada pencemaran PM dan juga membantu penyelidikan seterusnya secara efektif dan ekonomi.

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a_j	Wavelet scale
a_o	Smallest wavelet scale
a, b	Mother wavelets controlled parameters
A	Area, m^2
$\bar{d}_{\mathrm{p}}$	Mean spherule diameter
D_f	Fractal dimension
f_a	Atmospheric factor
f_c	Factor
f_m	Engine factor
J	Largest scale in the wavelet transform
k_f	Fractal prefactor
n	Time index
N_c	Number of cycles
P	Engine brake power
P_o	Observed power
p_o	Corrected power
Q_f	Heating value of the test fuel (MJ/kg)
Q_{gross}	Gross heat release rate
Q_{net}	Net heat release rate
R	Characteristic gas constant
s_o	Smallest resolvable scale in the wavelet transform
t	Time (s)
T	Engine brake torque

LIST OF ABBREVIATIONS

ANOVA	Analysis of variance
ASTM	American Society of Testing Materials
ATDC	After Top Dead Center
BDC	Bottom Dead Center
BSFC	Brake-Specific Fuel Consumption
BTDC	Before Top Dead Center
BTE	Brake Thermal Efficiency
CN	Cetane number
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COI	Cone of influence
COV	Coefficient of variation
CWT	Continuous wavelet transform
DF	Degree of freedom
DI	Direct Injection
DS	Dry soot
EGR	Exhaust gas recirculation
EN	European Union fuel standard
F	Probability distribution in repeated sampling
GWS	Global wavelet spectrum
H	Hydrogen
HC	Hydrocarbon
IDI	Indirect Injection
IMEP	Indicated mean effective pressure

NOx	Oxides of Nitrogen
N	Number of Spherules
OH	Hydroxide
PAHs	Polycyclic Aromatic Hydrocarbons
PM	Particulate Matter
PM_{10}	Particulate matter with diameter less than 10 μm
$PM_{2.5}$	Particulate matter with diameter less than 2.5 μm
POME	Palm oil methyl ester
Pr	Weight of significance
RoHR	Rate of Heat Release
rpm	Revolution per minute
SD	Standard deviation
SOF	Soluble organic fraction
TDC	Top Dead Center
TSP	Total Suspended Particle
TEM	Transmission Electron Microscope
WPS	Wavelet power spectrum
WHO	World health organization
WT	Wavelet transform

CHAPTER 1

INTRODUCTION

1.1 PROJECT BACKGROUND

Owing to the significant growth of the population, transportation, and the basic industry sectors, the demand for fossil fuel continues to increase (Asif & Muneer, 2007). Its growth began as the Industrial Revolution in Europe took off in the 18th century since vast quantities of fossil fuel were used to power the economy. However, based on the report, it is becoming a global problem as crude oil stock is depleting and its price is increasing. Therefore, significant environmental problems can be seen as the consumption of fossil fuel increases. Based on a BP Statistical Review of World Energy in June 2014, the global primary energy consumption in 2013 accelerated by approximately 2.3% over 2012 despite stagnant global economic growth. Moreover, the consumption and production of all fuels increased, reaching record levels for every fuel type except nuclear power. Global consumption rose more rapidly than the production of each type of fossil fuel. In 2013, the data suggests that growth in global carbon dioxide (CO_2) emissions from energy use also accelerated, although it remained below average (BP, 2014).

On the other hand, global energy consumption will rise by 37% by 2040, whereas crude oil consumption is expected to rise from the current 90 million barrels a day to 104 million barrels a day. However, demand for oil will plateau by 2040 according to the International Energy Agency (IEA) in its latest World Energy Outlook released on November 12, 2014, in London. Interestingly, the report also stated that the global supply of crude oil, other liquid hydrocarbons, and biofuels is expected to be sufficient to meet world demand for liquid fuel for at least the next 25 years. However, there is substantial uncertainty about the levels of future liquid fuel supply and demand. After the oil crises in the 1970s and 1980s, much of the debate about world oil markets focused on the limitations of supply (Birol, 2014).

According to Malaysia Energy Commission 2014, the total primary energy supply in Malaysia increased by 5.9% in 2012 compared to 3.2% during 2011. The production of crude oil growth was motivated by a 2.8% increase from 28,325 kilotonnes of oil equivalent (ktoe) in 2011 to 29,115 ktoe in 2012. Accordingly, the final energy consumption in 2012 also increased by 7.5%, which is 46,711 ktoe compared to 4.8% in 2011. The transportation sector provided the highest energy demand, which contributed 36.8%, followed by the industrial sector at 29.8%, the non-energy sector at 16.0%, the residential and commercial sectors at 15.1%, and the agriculture sector at 2.3%. Furthermore, in 2012, the total final energy consumption of petroleum products increased by 3.4%, with the major increases coming from kerosene and fuel oil. Final consumption of kerosene increased by 100.1%, whereas the final consumption of fuel oil increased by 85.5%. In a nutshell, petrol and diesel are the largest contributors to the total consumption of petroleum products with 36.2% and 35.6%, respectively, as illustrated in Figure 1.1 (Energy Commission, 2014).

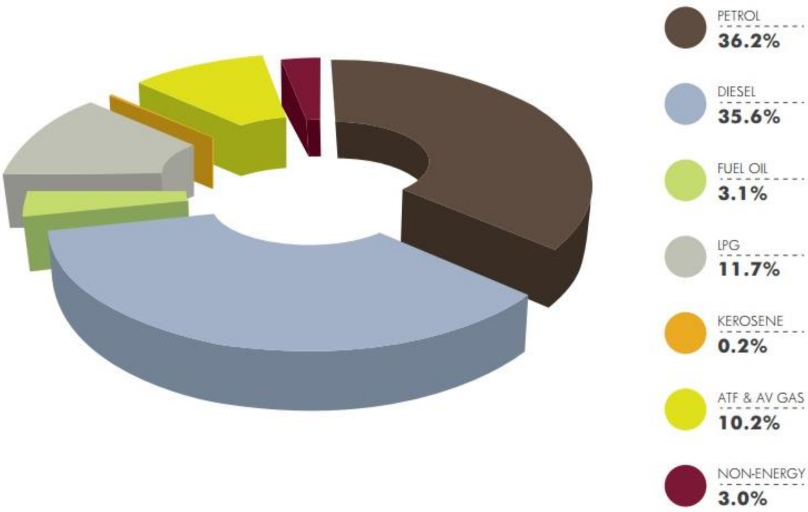

Figure 1.1: Final consumption of petroleum products

Source: Energy Commission (2014)

One of the main contributors to air pollution is the diesel engine. However, diesel engines are attractive power units used widely in many fields because of their great advantages over gasoline engines such as lower fuel consumption, lower carbon monoxide emissions, better torque characteristics, and higher reliability (Heywood, 1988; Stone, 1999). These characteristics make diesel engines the main contributor to total petroleum consumption. In contrast, owing to its lean-burning nature and high temperatures and pressures in the combustion process, diesel engines are the main contributors to air pollution for a large amount of emissions, especially particulates and nitrogen oxides (NOx) (Heywood, 1988). However, the trade-off trend between NOx and particulate matter (PM) in diesel combustion is not yet completely solved. One of the solutions identified by many researchers is to replace diesel fuel with an alternative fuel. Many agree that this solution can solve the problem of diesel emissions and also reduce dependence on crude oil. Thus, controlling these emissions is one of the most important aspects of modern air quality management.

Biodiesel is increasingly used as an alternative fuel and is becoming important owing to environmental and energy concerns. Besides, the Ministry of Plantation Industries and Commodities of Malaysia (MPIC, 2014) implement the B7 programme for the subsidized sector beginning in November 2014. B7 involves the blending of 7% palm biodiesel with 93% petroleum diesel. The implementation of the B7 programme would consume 575,000 tonnes of biodiesel, which would contribute towards a savings of 667.6 million litter of diesel a year (MPIC, 2014). Biodiesel, which is considered to be a low-carbon fuel, can be blended with different proportions and directly used in diesel engines without modification. In fact, it has been found that engines fuelled by biodiesel run successfully for longer durations. Moreover, the performance and emissions characteristics are also quite comparable to those of petroleum-based diesel fuel (Gopal et al., 2014).

Research has shown that diesel engines fuelled with palm oil could decrease the emissions produced in terms of smoke, PM, hydrocarbon, sulphur oxide, and carbon monoxide (Kumar & Chauhan, 2013; Lapuerta et al., 2008). However, there are growing concerns surrounding the negative impact of PM emissions from diesel engines on human health and the environment. Moreover, since the great smog of 1952 in

London, tremendous research on adverse health effects of air pollution have been recorded and have led to several changes in practices and regulations, including Clean Air Acts in most countries (Davis, 2002). Thus, many scientists and policy makers have worked together to solve the problems from different perspectives. The investigation has included the epidemiological and the toxicological effect of airborne pollutants. Diesel vehicles contribute significantly to the particulate air pollution problem, especially in metropolitan areas of developing Asian countries (Jin et al., 2014). As depicted in Figure 1.2, the size of the particle determines where it will deposit in the human respiratory tract when inhaled (Home Air Purifier Expert, 2010). Moreover, Peng et al. reported that PM with a size of 10 µm (PM_{10}) can enter the lungs and cause health problems ranging from coughing and wheezing to asthma attacks and severe bronchitis to high blood pressure and heart attacks. Similarly, PM that is 2.5 µm ($PM_{2.5}$) or smaller tends to penetrate the lungs, causing damage to the alveoli tissues and resulting in coughing and other severe respiratory problems for individuals with asthma or heart diseases. Smaller particles with a diameter less than 100 nm may pass through the lungs and affect other vital organs such as the brain (Organization, 2013; Peng et al., 2008).

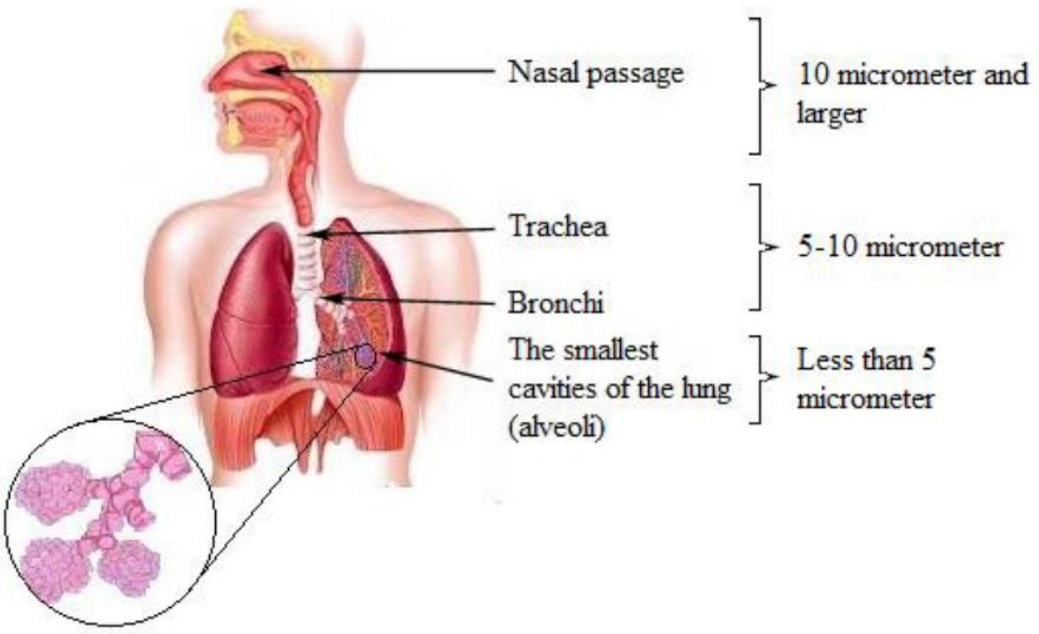

Figure 1.2: PM deposition in the human respiratory tract

Source: Home Air Purifier Expert (2010)

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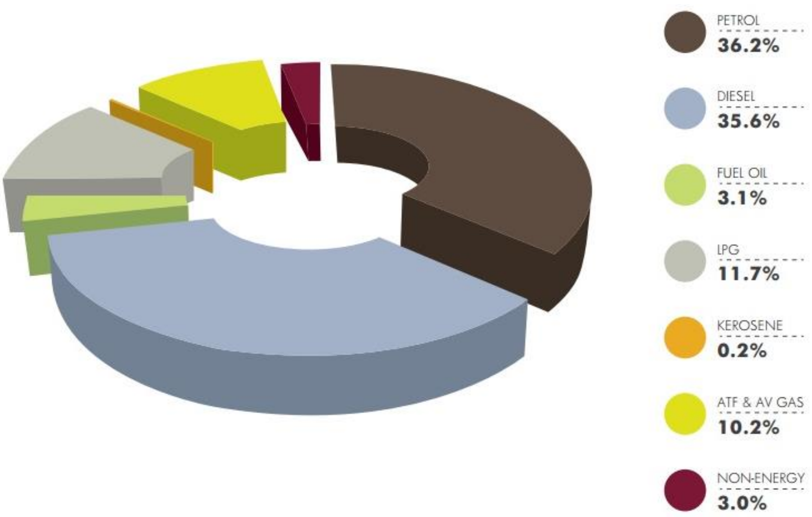

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CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

This chapter discusses the adopted methods and procedures in this study. Experimental and numerical work was performed in order to determine the blended fuel properties, diesel engine characteristics operating on different blended fuels, and particulate matter (PM) characteristics. The experimental setup and facilities utilised for the fuel property measurement, PM measurement, engine testing, and data acquisition system are presented. The modelling of the engine cyclic variation has also been presented in the numerical work procedures. In addition, a detailed explanation has been given on the operating test conditions and PM analysis. The engine cyclic variation modelling based on the in-cylinder pressure time series using the coefficient of variations and wavelet analysis approaches are also presented.

3.2 STRATEGY OF FRAMEWORK

Figure 3.1 illustrates the flowchart of the framework strategy for the current research methodology. There are two main components of the experimental work—PM characteristic measurement and engine testing—in addition to the engine cyclic variation modelling. According to this framework, the results are clarified in a logical manner.

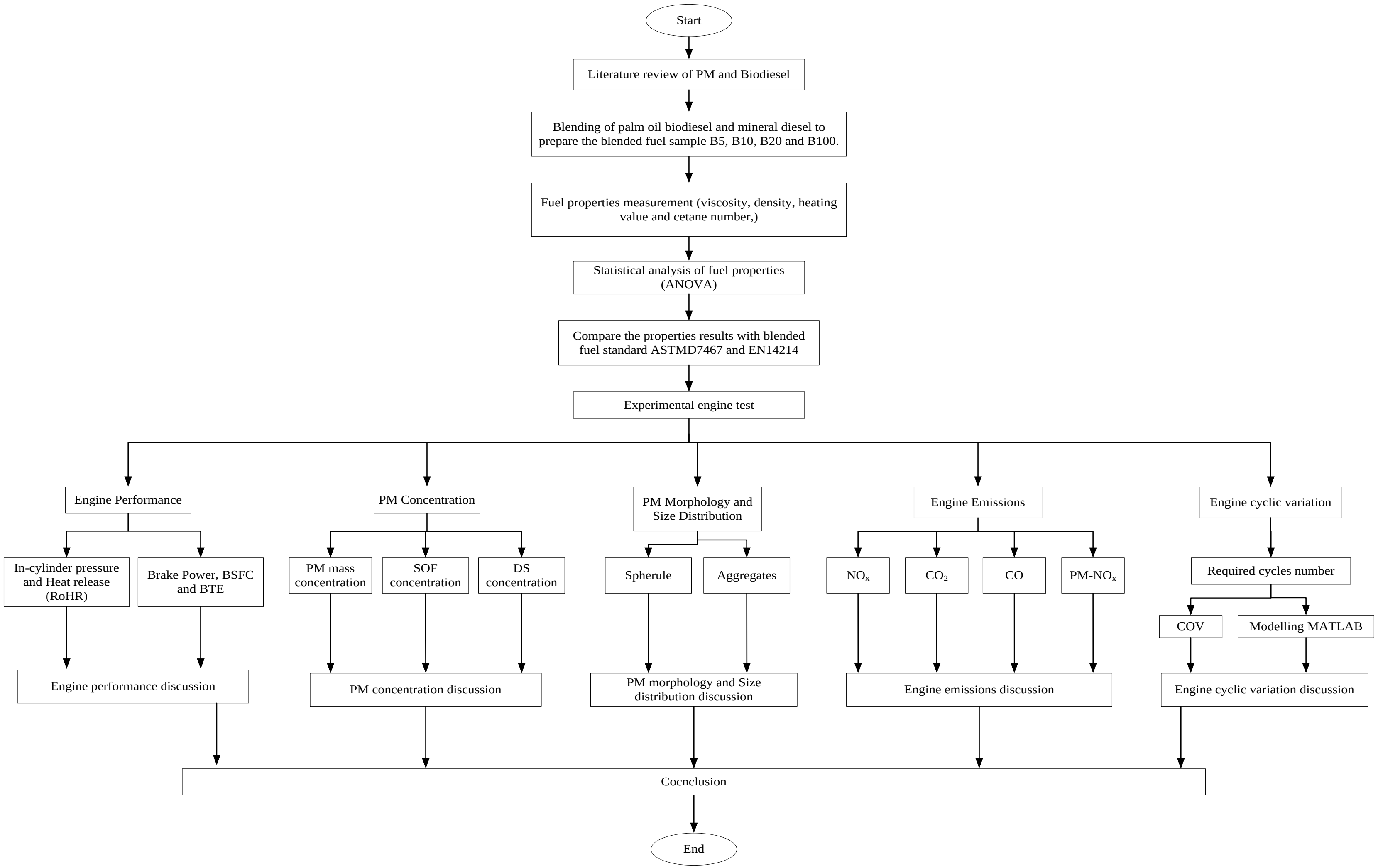

Figure 3.1: Flowchart of analysis

3.3 ENGINE TESTING APPARATUS

This section describes the setup of the experimental facilities. The experimental setup includes the experimental engine test rig and the instrumentation for measurement, including the in-cylinder pressure, fuel flow, engine speed, and engine torque. Moreover, a brief description of the data acquisition system and sensor integration is also provided.

A detailed schematic diagram of the experimental setup of the main components is presented in Figure 3.2. The experimental tests were conducted in the Engine Performance Laboratory, Faculty of Mechanical Engineering, Universiti Malaysia Pahang. Figure 3.3 shows the various components of the experimental engine test rig.