CERTIFICATION OF APPROVAL

**Combustion of Diesel and Syngas Mixtures in a 2-Stroke Diesel Engine**

by

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Approved by,

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# CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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EVA SARAH BT ZAKARIA

# ABSTRACT

Biomass is fast becoming the new era of technology due to the reduction of fossil fuel in the coming generation. Biomass can be converted to useful materials through the process of gasification. This process will in turn produce syngas or producer gas. Syngas can be used in many applications such as to produce methanol as well as to generate electricity. This study focuses on the application of syngas in internal combustion engine to generate power. Researchers have studied that there is a fluctuation of syngas produced from gasification process. This fluctuation creates a problem whereby it is difficult to study the effects of changing parameters under real condition. The fluctuation is due to many factors such as operating conditions of the gasifier as well as the types of feedstock used. A solution would be to fix the content of nitrogen, carbon dioxide, and hydrogen in a mixture which represents the syngas as a whole.  A two-stroke diesel engine was used to evaluate the performance of syngas-diesel mixture. Three conditions was evaluated at three conditions which were by using diesel only, diesel and syngas mixtures with Composition A which consisted of 56.02% nitrogen, 40.01% carbon dioxide, and 3.97% hydrogen and lastly diesel and syngas mixtures with Composition B which consisted of 75.70% nitrogen, 19.92% carbon dioxide, and 4.38% hydrogen. The general findings were Composition B showed a higher power output and brake thermal efficiency as well as lower exhaust temperature.

# ACKNOWLEDGEMENT

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# ABBREVIATIONS

| | |
|---|---|
| HP | Horse Power |
| HC | Hydrocarbon |
| ICE | Internal Combustion Engine |
| MPOB | Malaysian Palm Oil Board |
| NOx | Nitrogen oxide |
| SREP | Small Renewable Energy Power |
| AR4 | The Fourth Assessment Report |

# NOMENCLATURES

| | |
|---|---|
| $T_a$ | Ambient Temperature ($^oC$) |
| N | Angular Velocity (rad/s) |
| $\eta_B$ | Brake Thermal Efficiency (%) |
| $P_B$ | Brake Power (kW) |
| CV | Calorific Value (kJ/kg) |
| $\rho_m$ | Density of Mixture ($kg/m^3$) |
| $T_e$ | Exhaust Temperature ($^oC$) |
| $\dot{m}_f$ | Mass Flow Rate of Fuel (kg/s) |
| $\dot{m}_g$ | Mass Flow Rate of Gas (kg/hr) |
| $\dot{m}_m$ | Mass Flow Rate of Mixture (kg/s) |
| $sg_f$ | Specific Gravity of Fuel ($kg/m^3$) |
| $V_s$ | Swept Volume ($m^3$) |
| T | Torque (Nm) |
| $\eta_V$ | Volumetric Efficiency (%) |
| $\dot{V}_g$ | Volume Flow Rate of Gas (l/min) |

# CHAPTER 1
# INTRODUCTION

## 1.1 Background of Study

Day by day, global warming is becoming a great threat to the earth and fossil fuel is depleting. These problems have generated interest for renewable energy as a solution to stop global energy and promote sustainable development (Shuit et al, 2008). Biomass is one of the apparent interests among developing and industrialized countries as a renewable energy.

In Malaysia, the Fifth Fuel Policy was introduced in 2001 under the 8$^{th}$ Malaysia Plan. In this plan, renewable energy was announced as the fifth fuel in the energy supply mix. This is to supplement the supply from conventional energy sources. The renewable energy resources that was promoted according to priority were biomass, biogas, municipal waste, solar and mini-hydro. The Policy was implemented through the SREP Programme. It was introduced in May 2001 in conjunction with the Fifth Fuel Policy. The objective of the programme is to encourage small renewable energy power producers to generate electricity and sell the energy to national utility company. Thus, there is support from the government to invest in alternative energy (Chin et al, 2006).

Biomass is one the alternative energy that can be exploited in Malaysia. Biomass materials can be classified into four categories which are woody plants, herbaceous plants or grasses, aquatic plants and manures. In Malaysia, million hectares of land is occupied with palm oil plantation (Shuit et al, 2008). Palm oil waste is a very promising alternative as a source of raw materials for biomass. This is due to the fact that it is easily available and there is a need to dispose the waste with less cost. Figure 1.1 indicates that 62% of total agriculture land use in Malaysia is for palm oil. This shows that there are abundant of palm waste which can be used in the biomass sector.

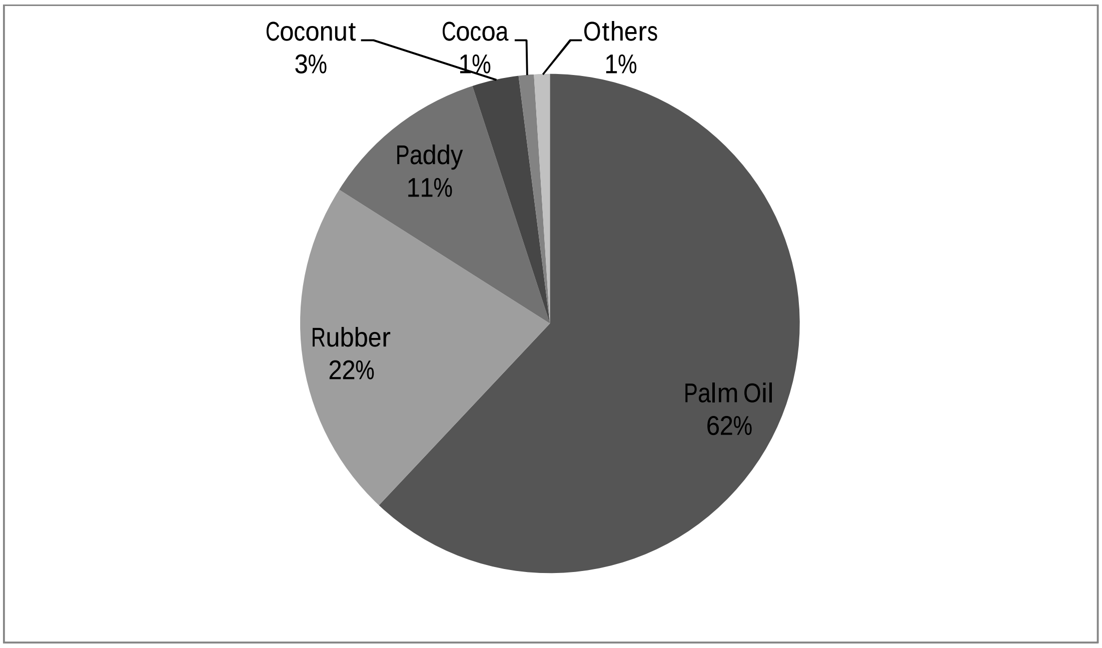


Figure 1.1: Percentage of agriculture land use in Malaysia in 2003 (MPOB, 2006)

Biomass gasification means incomplete combustion of biomass resulting in the production of combustible gases consisting of carbon monoxide (CO), hydrogen ($H_2$), and traces of methane ($CH_4$) (Sagitov, 2008). This group of gases are called syngas. Syngas has few applications such as a substitution for furnace oil in direct gasification processes and as a feedstock to generate methanol. One other application that is also generating interest is applying the syngas in internal combustion engine to generate power.

## 1.2 Problem Statement

Malaysia is one of the largest producers of palm oil and this occurs as a result of large plantation of palm oil trees (Muhammad, 2008). The oil palm fronds emanating from these palm oil trees are normally seen as wastes and they are being disposed in an uncontrolled manner. Technologies with improved efficiencies are needed to properly treat these tremendous amounts of wastes. Gasification is one of the possible technological options that could optimally convert the energy in these wastes for power generation. These wastes can be gasified to produce syngas and can be applied as fuel in internal combustion engine.

It is anticipated that the chemical composition of biomass gas produced in a real gasifier fluctuate due to factors such as operating temperature, pressure and air fuel ratio (Rezaiyan and Cheremisinoff, 2005). Therefore, a solution to control the variation of syngas would be to utilize a controllable composition of imitated syngas for power generation. By knowing the composition of imitated syngas that gives optimum engine performance, it will help to determine the appropriate operating conditions of gasifier and feedstock that will produce good composition of syngas.

### 1.3 Objective and Scope of Study

The objective of this research work was to characterize the combustion of syngas-diesel mixtures in a two-stroke diesel engine. The study involves evaluating the performance and emission of the engine as well as determining the appropriate composition of syngas that gives good combustion performance. The scope of this study was to vary the composition of syngas and compare the engine performance to see which composition of syngas is the most beneficial to the power generation.

# CHAPTER 2
# LITERATURE REVIEW AND THEORIES

Climate change and global warming are the most pressing global environmental problem facing humanity. Scientific data showed that hundreds of millions of people could lose their lives if average global temperatures increase by more than 2°C (Friends of the Earth, 2006). In addition, up to one million species of animals and plants are currently at the threat of extinction (Friends of the Earth, 2006). The rise of earth's temperature has caused many environment problems such as flooding, hurricanes and droughts. Other detrimental effects of global warming include increment in sea level and subsequently submerging of lowlands, deltas and island, changing of weather pattern, frequent rainstorms and drier soils as well as changing of water supplies because of unpredictable weather (Hassan et al. 2005).

According to The Fourth Assessment Report (AR4) which was released on 17 December 2007 of United Nation Intergovernmental Panel on Climate Change (IPCC), global warming which was observed over the last 50 years is likely due to increase of greenhouse of gas emission such as carbon dioxide, methane and nitrous oxide. This increasing of carbon dioxide concentration is primarily due to fossil fuel. Thus, a solution to overcome these toxic emissions is to substitute fossil fuel with renewable energy.

## 2.1 Biomass

Sims (2002) states that biomass can be defined as recent organic matter originally derived from plants as a result of the photosynthetic conversion process, or from animals, and which is destined to be utilized as a store of chemical energy to provide heat, electricity, or transport fuels. Biomass can be produced from combustion process, gasification technology, pyrolysis, and liquefaction.

Malaysia is the world second largest producer and exporter of palm oil in 2006 (U.S Department of Agriculture, 2007). Palm biomass acts as the main source of energy. The oil palm industry leaves behind large amount of biomass from its plantation activity. According to MPOB (Figure 2.1), 94% of biomass resources are from palm oil while the remaining percentages are from wood, sugar cane and rice. Thus, oil palm fronds can be use as a raw material for biomass which can be converted to commercial products such as animal food, fertilizer, absorbent, and biofuel.

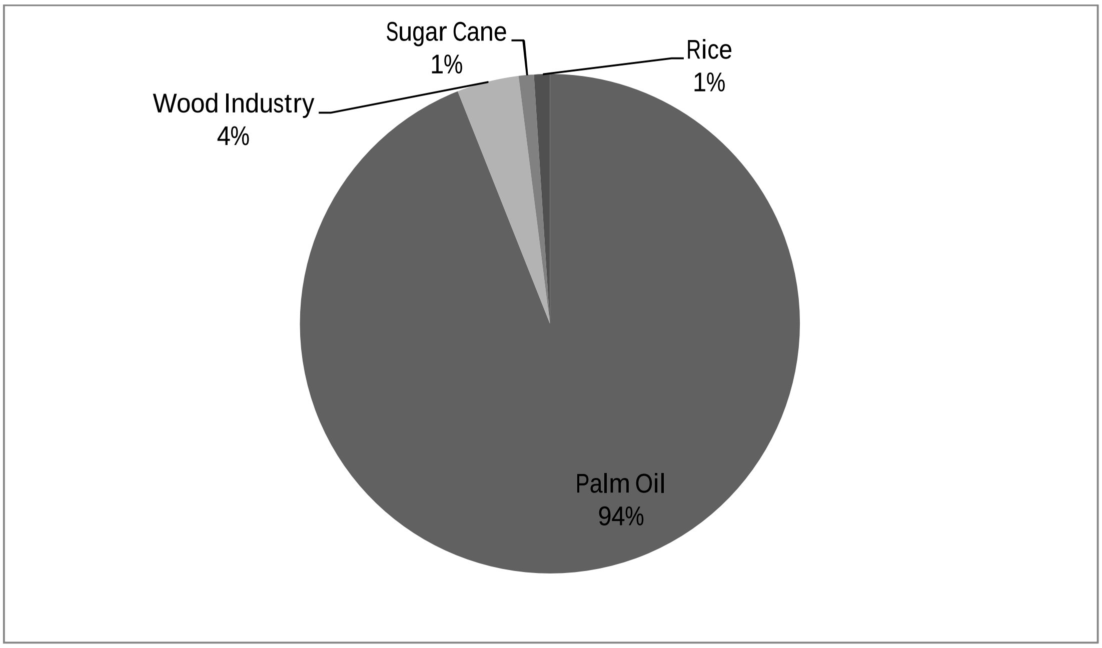


Figure 2.1: Agriculture waste as biomass resources (MPOB, 2006)

## 2.2 Gasification

Gasification is a process for converting carbonaceous materials to a combustible or synthetic gas. It involves the reaction of carbon with air, oxygen, steam, carbon dioxide, or a mixture of these gases at 1300$^{o}$F or higher to produce a gaseous product (Rezaiyan and Cheremisinoff, 2005). A biomass gasification system consists primarily of a reactor into which fuel is fed along with a limited supply of air (Stassen and Knoef, 1993). The resulting chemical breakdown of the fuel and internal reactions results in a combustible gas usually called syngas.

Depending on the gasification process, reactions that take place in a gasifier include (Rezaiyan and Cheremisinoff, 2005):

(1) $C + O_2 \rightarrow CO_2$
(2) $C + ½O_2 \rightarrow CO$
(3) $H_2 + ½O_2 \rightarrow H_2O$
(4) $C + H_2O \rightarrow CO + H_2$
(5) $C + 2H_2O \rightarrow CO_2 + 2H_2$
(6) $C + CO_2 \rightarrow 2CO$
(7) $C + 2H_2 \rightarrow CH_4$
(8) $CO + H_2O \rightarrow H_2 + CO_2$
(9) $CO + 3H_2 \rightarrow CH_4 + H_2O$
(10) $C + H_2O \rightarrow ½CH_4 + ½CO_2$

The gasification agent and the gasifier operating temperature and pressure affects the chemical composition, heating value and the end use applications of the gasifier product gas. There are also other factors that can affect the quality of the product gas such as the feedstock composition, feedstock preparation and particle size, reactor heating rate, and plant configuration (Rezaiyan and Cheremisinoff, 2005).

### 2.3 Syngas and Its Application in Internal Combustion Engine

Syngas is a mixture of hydrogen and carbon monoxide that can be converted into fuels such as hydrogen, natural gas and methanol. Syngas can also be used as a fuel to generate electricity and steam or as a chemical building block for the petrochemical and refining industries. Electricity generated from syngas is usually equipped with gas turbine engine or reciprocating engine.

Internal combustion engines (ICE) are one of the most widely used prime movers for biomass fuels. The advantages of ICEs include readily available over a wide size range, fast start-up, good part-load efficiency, reliability and long life. Sims (2002) mentioned in his book about several projects in European countries as well as the United States that uses biomass gasifier with ICEs.

For example, in the UK a Fluidyne $30kW_e/60kW_{th}$ downdraught gasifier was connected to an ICE generator set and fuelled by short-rotation coppice willow. The system was used to provide electricity and heat to a single farm and to two or three small adjacent farms. The surplus heat produced was either used for wood chip drying or dumped. The system was feasible in terms of energy but there were mechanical problems such as bridging the biomass fuel in the hopper and inefficient operation of the gas-cleaning chain (Sims, 2002).

In Northern Ireland, a downdraught gasifier with the capacity to fuel a dual-fuel gas/diesel engine driving a $100kW_e$ induction-type generator was tested. The engine was designed to operate on 90% gas, with the diesel fuel providing the necessary ignition. It was installed in a cogeneration configuration supplying 120 $kW_{th}$ for a central heating system and $80kW_{th}$ for drying the incoming short-rotation willow coppice fuel. Several problems were identified such as fuel variation characteristics and gas clean-up (Sims, 2002).

Meanwhile in the US, Bechtel National Inc. did a feasibility studies on a commercial KC gasifier (800 $kW_e$ and $1600kW_{th}$) and V-16 engine with a turbo-compressor and electronic ignition. The gasifier was tested satisfactorily utilizing a wide of biomass fuels such as rice husks, straw, corn cobs, and switchgrass (Sims, 2002).

In Malaysia, combustion characteristics of a diesel engine using syngas were done by Zainal and Soid (2007). The engine used was a single cylinder Yanmar $5kW_e$ engine connected to a Cusson engine test bed. The result shows slightly lower thermal efficiency and lower power output. There was also an increase in CO emission due to incomplete combustion. Their research gives significant value to this study as it will be a good reference in terms of the result.

Based on a research conducted by Atnaw and Sulaiman (2008), a downdraft biomass gasification model was developed to study the effect of operating pressure, temperature and air fuel ratio in the syngas composition in terms of mass fraction. From the simulation results, it was found that the mass fractions of the major fuel components of the syngas; CO, $H_2$ and $CH_4$ are higher at lower air fuel ratio, higher oxidation temperature and lower operating pressure values below 5 bar. This shows that there is a fluctuation in composition of syngas. Therefore in this study, different sets of composition of syngas are tested to determine the composition that gives the best engine performance.

## 2.4 Theory and Calculations

### 2.4.1 Air Mass Flow

For a given air density the mass flow rate of air is proportional to the average velocity, so that the pressure drop across the viscous element is directly proportional to the flow rate. The pressure drop was measured by an inclined tube manometer, calibrated in milimeters of water. Figure 2.2 shows a typical calibration curve for air at 1013 mb and 20$^{o}$C.

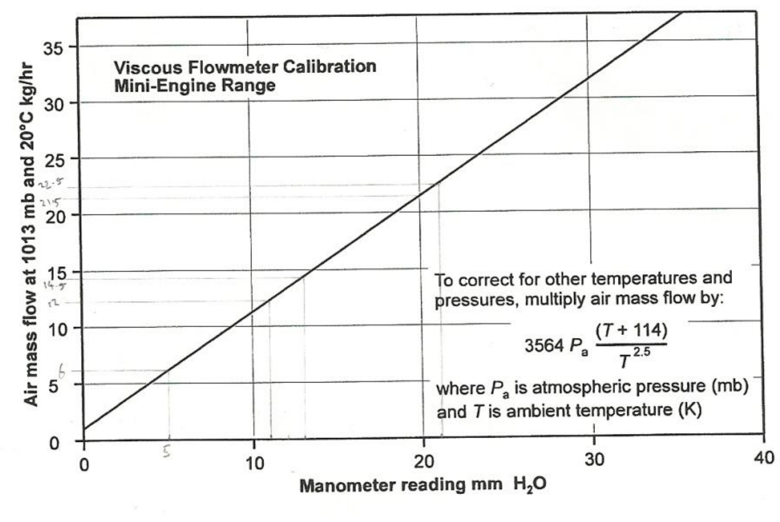


Figure 2.2: Viscous Flow Meter Calibration

Once the manometer reading was obtained, the graph in Figure 2.2 was used to determine the air mass flow in kg/hr. For other temperature and pressure, multiply the air mass flow with the above equation to obtain the corrected air mass flow. The temperature and pressure during the experiment was at 27°C and at 1013mb. Thus, the air mass flow obtained from Figure 2.2 was multiplied with Equation 2.1 to obtain the corrected air mass flow.

$$\dot{m}_{a,corrected} = \dot{m}_a \times 3564 \times \frac{(300+114)}{300^{2.5}} \tag{2.1}$$

### 2.4.2 Fuel Mass Flow

An 8 ml pipette was used to obtain the fuel mass flow rate. The fuel consumption was determined by measuring the time (t) taken for the engine to consume 8 ml of fuel. The specific gravity for water and diesel was assumed to be 1000 kg/m$^3$ and 0.84 kg/m$^3$ respectively.

$$\dot{m}_f = \frac{sg_f \times 8 \times 10^{-3}}{t} \times 3600 \tag{2.2}$$

### 2.4.3 Brake Power

The power output was calculated from the torque by multiplying by the angular velocity in radians per second. Because the dynamometer acts as a brake on the engine, the power at the output shaft is referred to as the “brake power”.

$$P_B = \frac{2\pi N}{60} \times T \tag{2.3}$$

### 2.4.4 Mass Flow Rate of Gases

The volume flow rate of each gas was obtained from the flow meter. The mass flow rate was then calculated from Equation 2.4.

$$\dot{m}_g = \dot{V} \times \rho_g \qquad (2.4)$$

The mass flow rate of mixture going into the engine was then calculated by adding the mass flow rate of air and mass flow rate of each gas together.

$$\dot{m}_m = \dot{m}_a + \dot{m}_{CO2} + \dot{m}_N + \dot{m}_H \qquad (2.5)$$

### 2.4.5 Air-Fuel Ratio

In this study, the air and syngas was sucked into the engine through the air intake. Thus, instead of calling air/fuel ratio, in this study it was called the mixture-fuel ratio. This term refers to the ratio of mixtures and fuel present during the combustion. The ratio can be calculated using Equation 2.6.

$$Mixture - Fuel\ Ratio = \frac{\dot{m}_m}{\dot{m}_f} \qquad (2.6)$$

### 2.4.6 Density of Gas Mixtures

Calculation of density of gas mixtures requires a few steps. First, the volume percent of each gas was calculated from Equation 2.7. Then, assuming 100% volume equals to 100 litres and working at STP, mass of each gas was calculated from the molar mass (*M*). At STP, the temperature and pressure was given as 273K and 1 atm respectively. The current condition was 300K and 1 atm. Using ideal gas law, the volume at the current condition was obtained from Equation 2.9. Finally, the density was calculated from Equation 3.0.

$$Vol\% = \frac{\dot{V}_g}{\sum \dot{V}_g} \times 100 \qquad (2.7)$$

$$Given\ 1\ mol = 22.4\ litres$$

$$m_g = \frac{\%Vol_g}{22.4} \times M_g \tag{2.8}$$

$$\frac{P_1 \times V_1}{T_1} = \frac{P_2 \times V_2}{T_2} \tag{2.9}$$

$$Density\ of\ gases = \frac{\sum m_g}{V_2} \tag{2.10}$$

### 2.4.7 Volumetric Efficiency

During each cycle, it was assumed that an engine can draw in a mass of air equal to the swept volume multiplied by the ambient air density. In this case, since the mixture of syngas and air was swept into the cylinder, the mass of mixture that was drawn in was equal to the swept volume multiplied by the density of mixture. The ratio of the actual mass flow to the ideal value is called the volumetric efficiency. Power output depends on the amount of air drawn into the cylinder, so any reduction in volumetric efficiency will reduce the power output. The formula to obtain the volumetric efficiency is shown below.

$$\eta_v = \frac{\dot{m}_m}{60N\rho_m V_s} \tag{2.11}$$

The symbol $\dot{m}_m$ refers to the mass flow rate of mixture which can be measured directly. Meanwhile, $\rho_m$ is the density of mixture. The swept volume is symbolized as $V_s$.

### 2.4.8 Brake Thermal Efficiency

For economic reasons, it is important to obtain the maximum work output from a given amount of fuel, that is, to obtain the maximum overall efficiency of energy conversion. This efficiency is expressed as the brake thermal efficiency and defined as:

$$\eta_B = \frac{\text{Actual power output}}{\text{Rate of heat input}} \tag{2.12}$$

If the rate of heat input is $\dot{m}_f \times \text{Calori ic Value } (CV)$, then

$$\eta_B = \frac{P_B}{\dot{m}_f \times CV} \tag{2.13}$$

The mass flow rate of fuel was obtained directly from the instrumentation unit. Meanwhile, the typical calorific value of diesel fuel is 39000 kJ/kg. The brake thermal efficiency accounts for all the losses which occur in the engine. It is therefore a very important measure of engine performance.

### 2.4.9 Percentage Heat Loss in Exhaust

An estimate of the heat lost to the exhaust can be made by measuring the difference between the exhaust ($T_e$) and ambient temperatures ($T_a$), and assuming a typical value of 1 kJ/kgK for the specific heat of the exhaust gases.

$$\text{\% Heat Loss in Exhaust} = \frac{\text{Heat loss in exhaust}}{\text{Heat supplied to the engine}} \times 100$$

$$\text{\% Heat Loss in Exhaust} = \frac{(\dot{m}_m + \dot{m}_f) \times (T_e + T_a)}{\dot{m}_f \times CV} \times 100 \tag{2.14}$$

# CHAPTER 3
# METHODOLOGY

This study consists of five parts. They are literature review, basic engine testing, installing of experimental rig, engine testing with syngas, and reporting. The flowchart below summarizes the whole process.

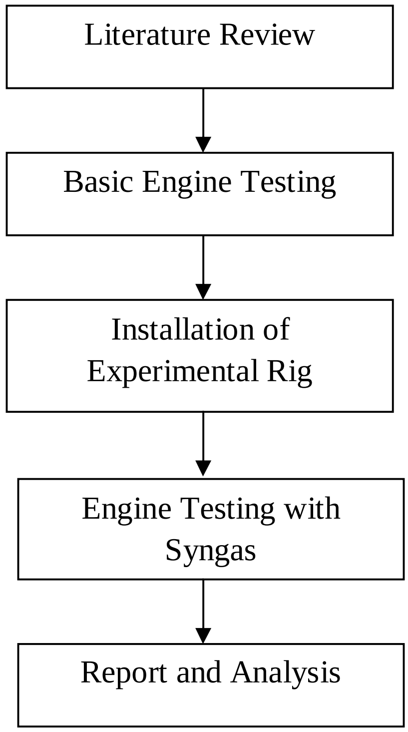


Figure 3.1: Flowchart of Methodology

The proposed project flow is shown in the Gantt chart in Appendix A, in which Semester 1 consists of mainly the literature research while in Semester 2 the setting up and experiment was conducted.

### 3.1 Basic Engine Testing

The engine that was used was a single cylinder Tecumseh 5HP diesel engine. The engine was connected to a hydraulic dynamometer and instrumentation unit. For this basic testing, diesel fuel was used to obtain the standard result without any modification done to the engine. Figure 3.2 shows the arrangement of the engine with instrumentation and dynamometer.

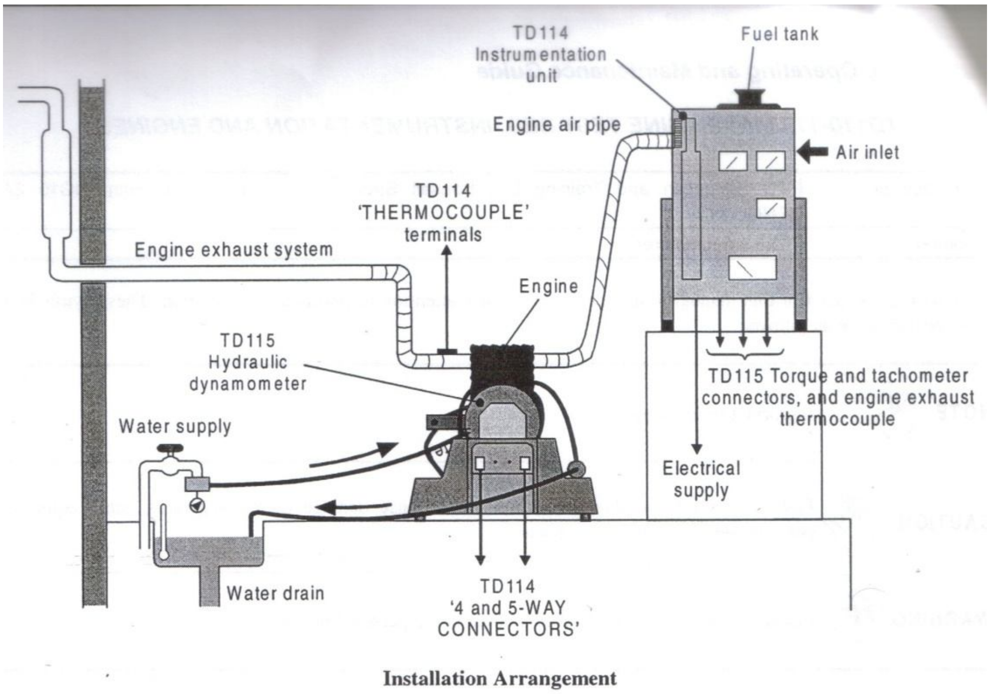


Figure 3.2: Installation Arrangement in UTP Block 15

### 3.1.1 Instrumentation Unit

The instrumentation unit was designed to stand beside the engine under testing. In addition to housing the instruments necessary for measuring the engine performance, it contains the fuel system and the airbox/viscous flow meter used to measure the consumption of air. The instrumentation unit was used to measure the torque, speed, exhaust temperature, fuel consumption, and air flow rate. A front view of the instrumentation unit is shown in Figure 3.3.

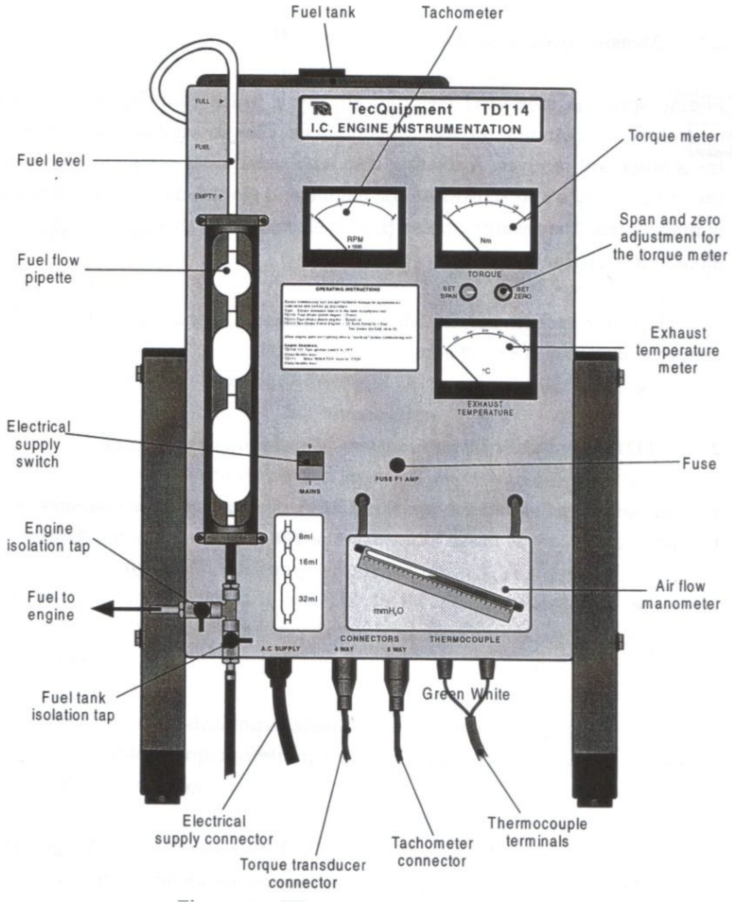


Figure 3.3: Instrumentation Unit in UTP Block 15

### 3.2 Design and Installation of Experimental Rig

The engine was not modified; instead, an experimental rig was attached to it. The rig consists of gas cylinders which are connected to the air intake valve of the engine. Pre-mixing of air and the gases occurred outside of the engine before entering the air intake valve. The whole rig and engine was placed at Block 15. The schematic diagram of the experimental rig is shown below.

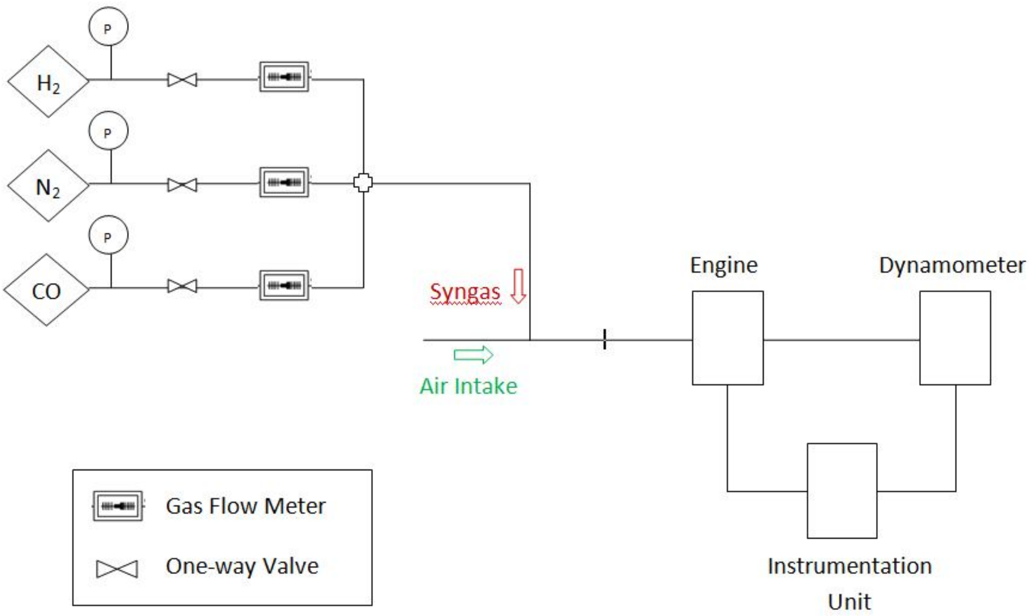


Figure 3.4: Schematic diagram of the experimental rig

Figure 3.5 shows the design of the part where the three gases will meet and mix before exiting as one gas mixture and then enters the engine. The part was fabricated out of carbon steel. Fittings were welded at all the four openings to prevent leakage.

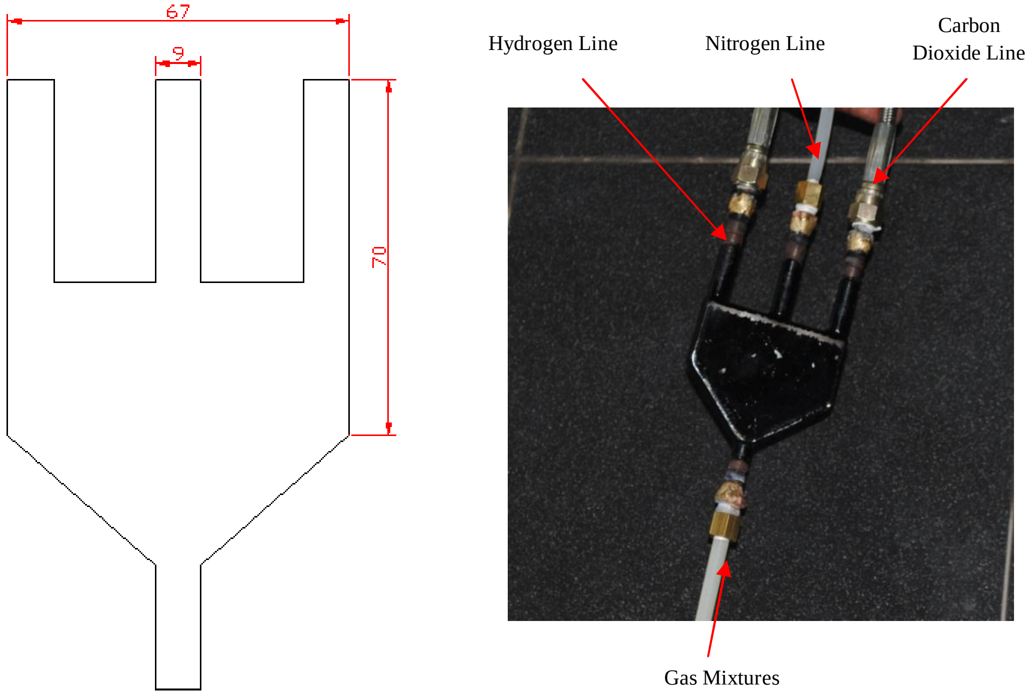


Figure 3.5: Design of a 3-way adapter (all units are in mm)

Figure 3.6 shows the design of the adapter which was used to connect the syngas tube and air tube to the engine. The syngas tube was a Teflon tube. The adapter was fabricated out of carbon steel.

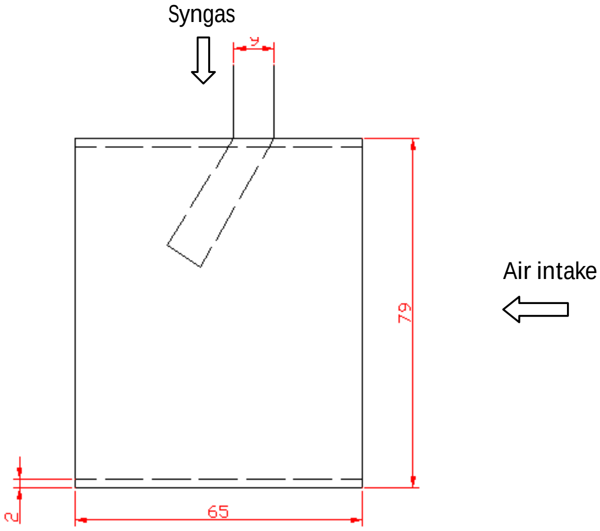


Figure 3.6: Design of the adapter for syngas and air flow (all units are in mm)

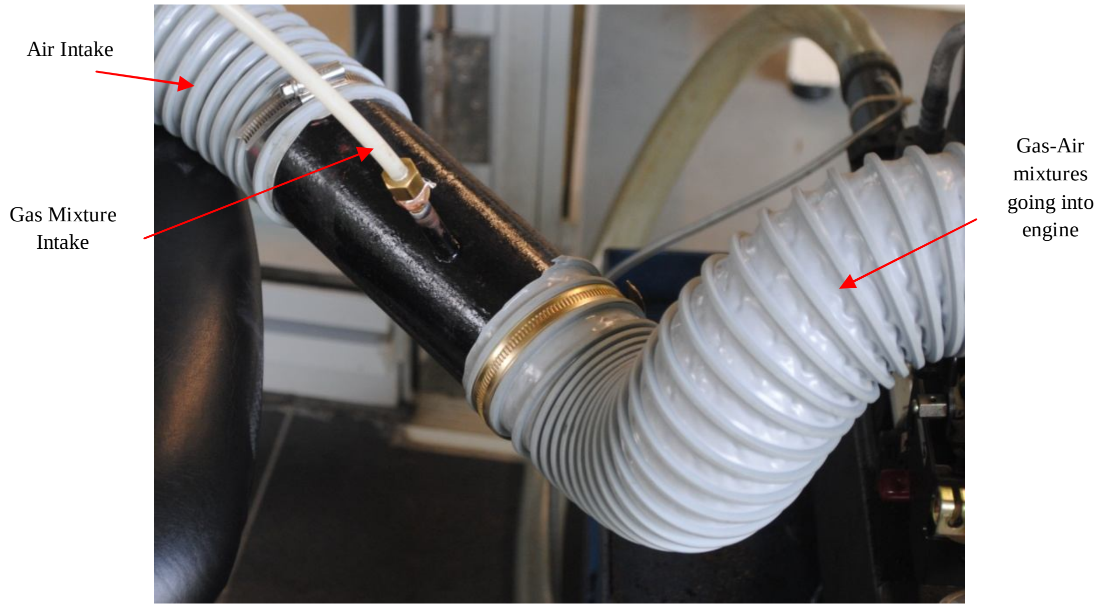


Figure 3.6: Design of the adapter for syngas and air

### 3.3 Engine Testing with Imitated Syngas

The test procedure using syngas was the same as the procedure done with diesel fuel. However, this time the rig was connected to the engine where the gases flow to the engine and combustion occured. The engine was started and switched to the highest speed. Once the engine has stabilizes, the nitrogen gas valve was opened to let the gas flow into the engine. Then, the carbon dioxide gas valve was opened followed by the nhydrogen gas valve. Hydrogen gas is very flammable thus, it must bethe last gas that flows into the engine. Next, the flow rate was recorded from the flow meter. The volume flow rate represents the amount of gas that entered the engine, hence it represents the composition of the gas. Then, the reading from the instrumentation unit was recorded. The speed was reduced and the reading was recorded again. In order to obtain different composition, the flow meter was adjusted. The reading at the instrumentation unit was recorded again for the new composition. Before shutting down the engine, the gas valve was closed first in the order it was opened which was hydrogen, carbon dioxide and finally nitrogen valve. The detailed procedure of the engine run is attached in Appendix B.

# CHAPTER 4
# RESULTS AND DISCUSSION

## 4.1 Engine Test Run

Results were taken at three conditions which were using only diesel, with diesel and syngas at Composition A, and with diesel and syngas at Composition B. Composition A consists of 56.02% nitrogen, 40.01% carbon dioxide, and 3.97% hydrogen. Composition B consists of 75.70% nitrogen, 19.92% carbon dioxide, and 4.38% hydrogen.

### 4.1.1 Test Results

Table 4.1 summarizes the result for combustion using only diesel. Calculations were done using equations specified in Chapter 2.

Table 4.1: Results for combustion using only diesel (with load)

| Parameters | Speed (rpm) | | | | |
|---|---|---|---|---|---|
| | **1800** | **2000** | **2200** | **2600** | **2800** |
| **Specific Gravity (diesel)** | 0.84 | 0.84 | 0.84 | 0.84 | 0.84 |
| **Barometric pressure (kPa)** | 101.3 | 101.3 | 101.3 | 101.3 | 101.3 |
| **Ambient temperature ($^oC$)** | 27 | 27 | 27 | 27 | 27 |
| **Air Density ($kg/m^3$)** | 1.177 | 1.177 | 1.177 | 1.177 | 1.177 |
| **Torque (Nm)** | 1.6 | 1.9 | 2.1 | 2.3 | 2.6 |
| **Brake power (kW)** | 5.03 | 6.63 | 8.06 | 10.44 | 12.71 |
| **Fuel; time for 8 ml (s)** | 137.6 | 111.3 | 96.6 | 82.1 | 67.8 |
| **Fuel mass flow rate (kg/hr)** | 0.176 | 0.217 | 0.25 | 0.295 | 0.357 |
| **Specific fuel consumption (g/kWh)** | 34.98 | 32.77 | 31.06 | 28.23 | 28.08 |
| **Air ($mmH_2O$)** | 9 | 11 | 12 | 15 | 18 |
| **Air mass flow rate (kg/hr)** | 8.97 | 10.75 | 11.65 | 14.78 | 17.02 |
| **Air/fuel ratio** | 51.01 | 49.46 | 46.51 | 50.17 | 47.7 |
| **Exhaust Temperature ($^oC$)** | 140 | 140 | 145 | 160 | 185 |
| **Volumetric efficiency (%)** | 0.682 | 0.736 | 0.725 | 0.778 | 0.832 |
| **Brake thermal efficiency (%)** | 2.639 | 2.817 | 2.972 | 3.27 | 3.287 |
| **% heat loss exhaust** | 15.07 | 14.62 | 14.37 | 17.45 | 19.73 |

Table 4.2 shows the result for combustion using diesel and syngas with Composition A. The composition was obtained from the volume flow rate of each gas where it was assumed that the rate of gas flowing through the flow meter is the amount of gas that went in to the engine. Table 4.3 summarizes the flow rate and volume percentage of Composition A.

Table 4.2: Results of combustion using diesel and syngas with Composition A

| Parameters | Speed (rpm) | | | |
|---|---|---|---|---|
| | 2200 | 2600 | 3000 | 3400 |
| Specific Gravity (diesel) | 0.84 | 0.84 | 0.84 | 0.84 |
| Barometric pressure (kPa) | 101.3 | 101.3 | 101.3 | 101.3 |
| Ambient temperature ($^oC$) | 27 | 27 | 27 | 27 |
| Air Density ($kg/m^3$) | 1.177 | 1.177 | 1.177 | 1.177 |
| Torque (Nm) | 1.75 | 1.8 | 2 | 2.2 |
| Brake power (kW) | 0.403 | 0.49 | 0.628 | 0.783 |
| Fuel; time for 8 ml (s) | 79 | 62.94 | 52.8 | 30.6 |
| Fuel mass flow rate (kg/hr) | 0.306 | 0.384 | 0.458 | 0.791 |
| Specific fuel consumption (g/kWh) | 759.5 | 784.3 | 729.2 | 1009 |
| Air ($mmH_2O$) | 9 | 11 | 12 | 15 |
| Air mass flow rate (kg/hr) | 8.968 | 10.75 | 11.65 | 14.78 |
| Air volume flow rate ($m^3/s$) | 0.002 | 0.003 | 0.003 | 0.003 |
| Mass flow rate gases (kg/hr) | 5.163 | 5.163 | 5.163 | 5.163 |
| Mass flow rate of mixture (kg/hr) | 14.13 | 15.91 | 16.81 | 19.95 |
| Mixture/fuel ratio | 46.15 | 41.4 | 36.69 | 25.23 |
| Exhaust Temperature ($^oC$) | 180 | 230 | 260 | 400 |
| Density of mixtures | 1.335 | 1.334 | 1.334 | 1.333 |
| Volumetric efficiency (%) | 0.349 | 0.332 | 0.304 | 0.319 |
| Brake thermal efficiency (%) | 0.122 | 0.118 | 0.127 | 0.091 |
| % heat loss exhaust | 5.664 | 8.484 | 10.32 | 19.83 |

Table 4.3: Composition A

| Gases | $H_2$ | $CO_2$ | N |
|---|---|---|---|
| Density ($kg/m^3$) | 0.082 | 1.831 | 1.145 |
| Volume Flow Rate (l/min) | 2.48 | 25 | 35 |
| Volume Flow Rate ($m^3/s$) | 4.13333E-05 | 0.000416667 | 0.000583333 |
| Mass Flow Rate (kg/s) | 3.38933E-06 | 0.000762917 | 0.000667917 |
| Volume Percentage | 3.97 | 40.01 | 56.02 |

Table 4.4 shows the result for combustion of diesel and syngas with Composition B while Table 4.5 shows the flow rate and volume percentage of Composition B.

Table 4.4: Results of combustion using diesel and syngas with Composition B

| Parameters | Speed (rpm) | | | |
|---|---|---|---|---|
| | 2200 | 2400 | 2800 | 3200 |
| Specific Gravity | 0.84 | 0.84 | 0.84 | 0.84 |
| Barometric pressure (kPa) | 101.3 | 101.3 | 101.3 | 101.3 |
| Ambient temperature ($^oC$) | 27 | 27 | 27 | 27 |
| Air Density ($kg/m^3$) | 1.177 | 1.177 | 1.177 | 1.177 |
| Torque (Nm) | 2.4 | 2.5 | 2.8 | 2.7 |
| Brake power (kW) | 9.215 | 10.47 | 13.68 | 15.08 |
| Fuel; time for 8 ml (s) | 95.4 | 83.88 | 68.72 | 50.32 |
| Fuel mass flow rate (kg/hr) | 0.254 | 0.288 | 0.352 | 0.481 |
| Specific fuel consumption (g/kWh) | 27.52 | 27.54 | 25.73 | 31.88 |
| Air ($mmH_2O$) | 9 | 11 | 12 | 15 |
| Air mass flow rate (kg/hr) | 8.968 | 10.75 | 11.65 | 14.78 |
| Air volume flow rate ($m^3/s$) | 0.002 | 0.003 | 0.003 | 0.003 |
| Mass flow rate gases (kg/hr) | 3.72 | 3.72 | 3.72 | 3.72 |
| Mass flow rate of mixture (kg/hr) | 12.69 | 14.47 | 15.37 | 18.5 |
| Mixture/fuel ratio | 50.04 | 50.18 | 43.65 | 38.49 |
| Exhaust Temperature ($^oC$) | 160 | 170 | 200 | 240 |
| Density of mixtures | 0.607 | 0.608 | 0.609 | 0.611 |
| Volumetric efficiency (%) | 0.688 | 0.718 | 0.653 | 0.686 |
| Brake thermal efficiency (%) | 3.354 | 3.352 | 3.588 | 2.895 |
| % heat loss exhaust | 4.413 | 5.412 | 6.973 | 10.37 |

Table 4.5: Composition B

| Gases | $H_2$ | $CO_2$ | N |
|---|---|---|---|
| Density ($kg/m^3$) | 0.082 | 1.831 | 1.145 |
| Volume Flow rate (l/min) | 2.2 | 10 | 38 |
| Volume Flow Rate ($m^3/s$) | 3.66667E-05 | 0.000166667 | 0.000633333 |
| Mass Flow Rate (kg/s) | 3.00667E-06 | 0.000305167 | 0.000725167 |
| Volume percentage | 4.38 | 19.92 | 75.70 |

### 4.2 Graphs and Discussions

From the three tables shown in Section 4.1, the engine performance can be evaluated from the exhaust temperature, brake power, mixture/fuel ratio, specific fuel consumption, brake thermal efficiency, volumetric efficiency, and percentage of heat loss through exhaust. This criterion was discussed further below.

#### 4.2.1 Exhaust Temperature

From the graph below, the exhaust temperature increased when syngas was added. This might be due to the incomplete combustion of the syngas in the combustion chamber. Some of the unburned fuel escapes into the exhaust manifold and combustion takes place in the exhaust manifold causing the high exhaust temperature. Composition A shows a relatively high exhaust temperature. This might be due to excessive $CO_2$ in the composition which did not combust in the cylinder.

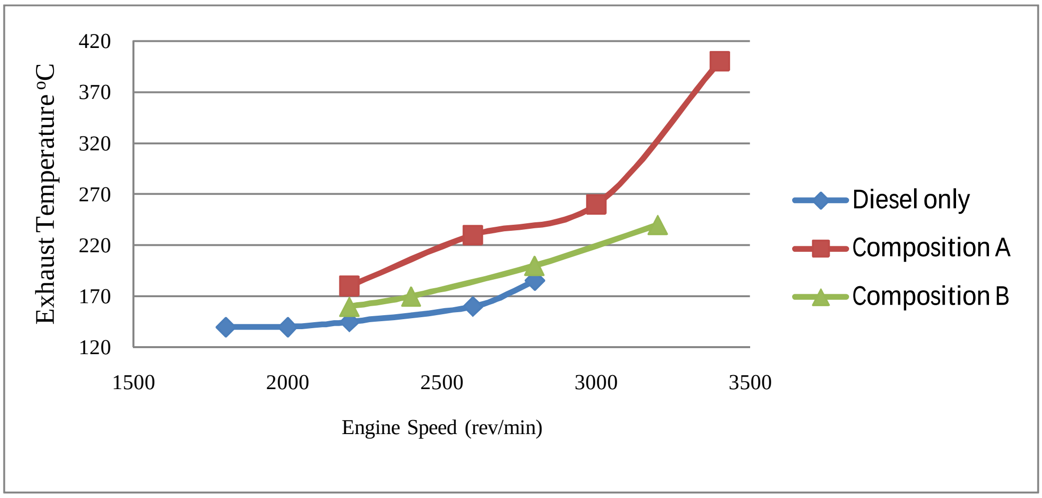


Figure 4.1: Variations of exhaust temperature with engine speed for different fuel compositions

### 4.2.2 Brake Power

Brake power refers to the power output of the engine. From Figure 4.2, Composition B produced the highest amount of power when compared to the other two conditions. It is expected that there would be power loss when using syngas gas due to its lower heating value when compared to heating value of diesel. However, that is not the case shown in Figure 4.2.

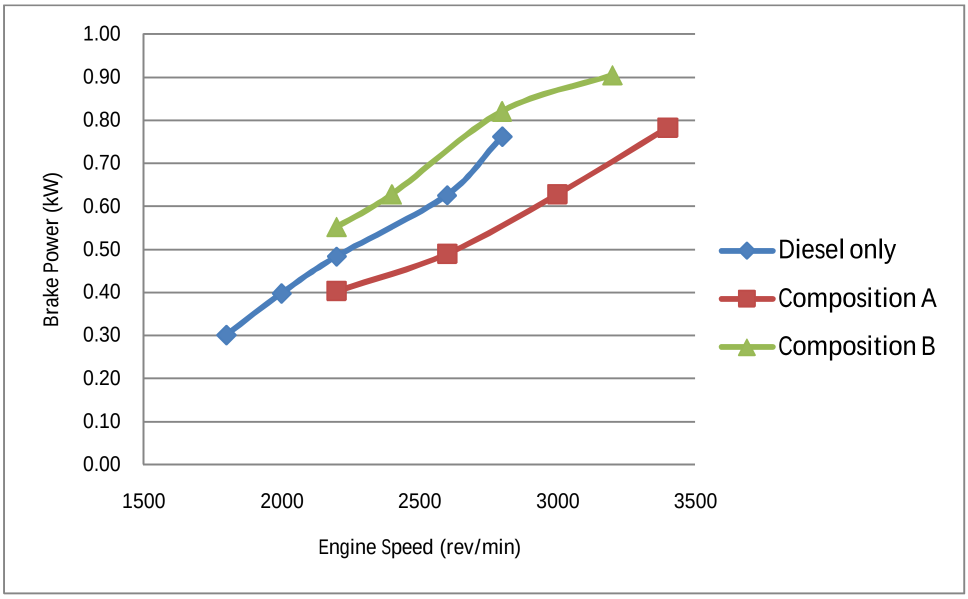


Figure 4.2: Variations of brake power with engine speed for different fuel compositions

### 4.2.3 Mixture-Fuel Ratio

The mixture-fuel ratio for Compositions A and B is lower than for diesel only. This indicates that Compositions A and B shows a rich mixtures. More fuel was present in the combustion chamber than air. Since there was more fuel than air, there were excess fuels which did not combust and instead flows to the exhaust and caused an increased in the exhaust temperature. This explains the high exhaust temperature of Composition A in Section 4.2.1.

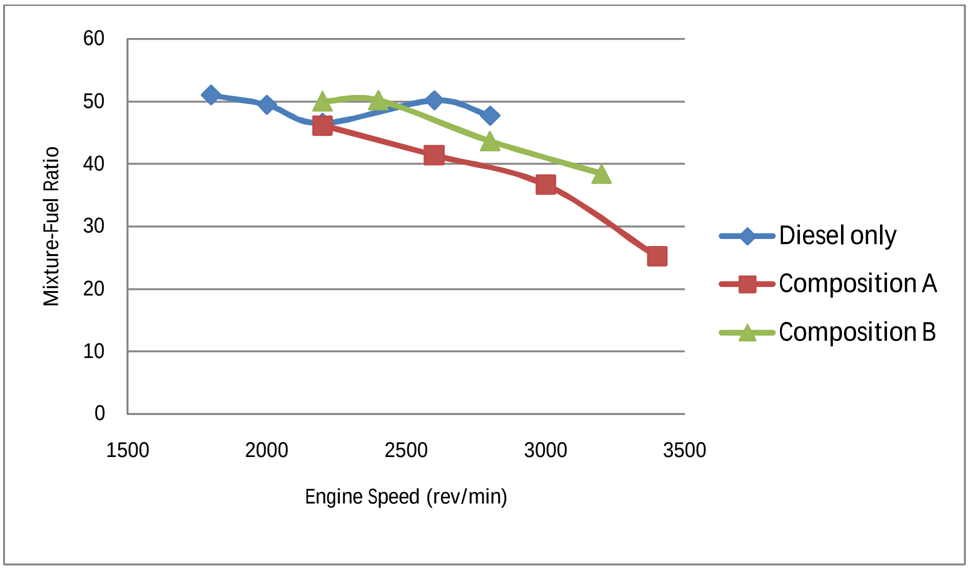


Figure 4.3: Variations of mixture-fuel ratio with engine speed for different fuel compositions

### 4.2.4 Specific Fuel Consumption

Figure 4.4 show that Composition A has very high specific fuel consumption. From Figure 4.2, Composition A also produces less power due to smaller heating value of syngas. Since the heating value of syngas is less than diesel, higher fuel consumption is needed for combustion. Composition B shows a very good characteristic because it has lower fuel consumption and produces a higher power output than the rest.

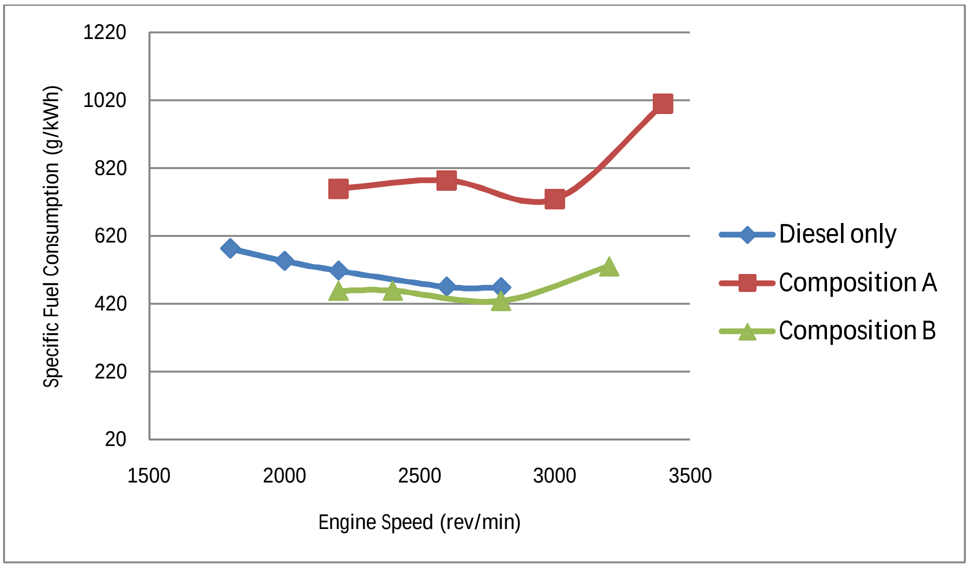


Figure 4.4: Variations of specific fuel consumption with engine speed for different fuel compositions

#### 4.2.5 Brake Thermal Efficiency

Brake thermal efficiency refers to the measure of the maximum overall efficiency of energy conversion. Equation 3.3 was used to calculate the brake thermal efficiency. Figure 4.5 shows that Composition B has the highest efficiency while Composition B has the lowest. This is due to the power produced where Equation 3.3 shows that efficiency depends on the brake power. Since Compositions A and B produced the highest and lowest power respectively, it proves the result in Figure 4.5.

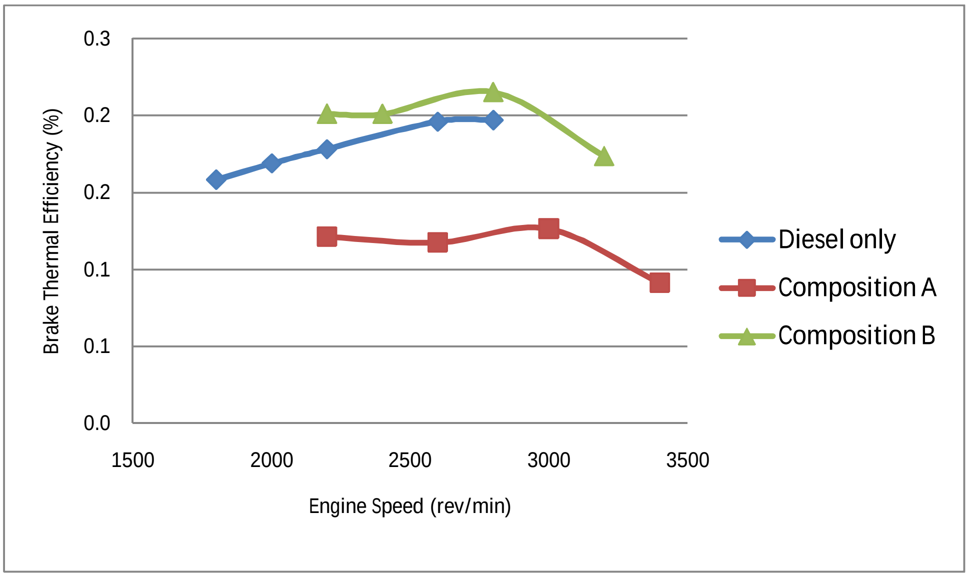


Figure 4.5: Variations of brake thermal efficiency with engine speed for different fuel compositions

#### 4.2.6 Volumetric Efficiency

Volumetric efficiency in this study refers to the amount of air n gas mixtures that the engine can draw in or specifically the ratio of the actual mass flow of air and gas mixtures to the ideal mass flow. The power output depends on the amount of air drawn into the cylinder, so any reduction in volumetric efficiency will reduce the power output. From Figure 4.6, Composition A has the lowest volumetric efficiency which means not much air and gas mixtures are sucked into the engine and leads to lower power output.

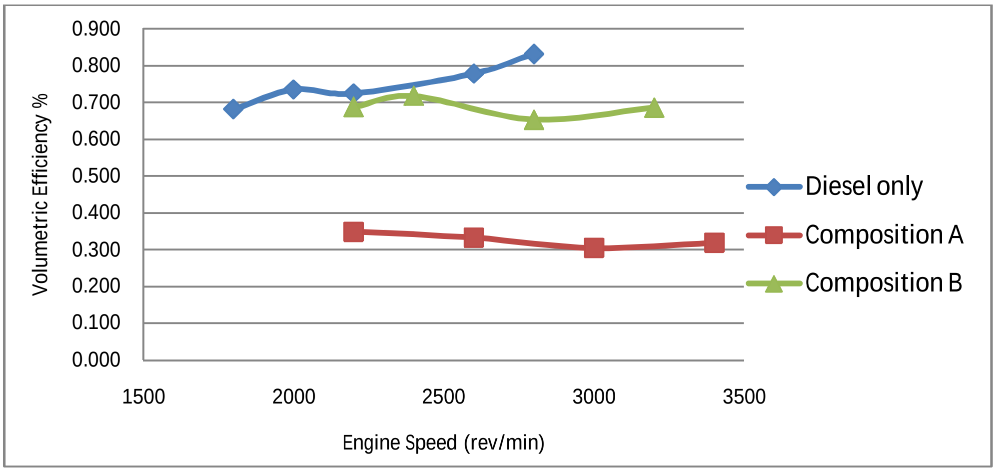


Figure 4.6: Variations of volumetric efficiency with engine speed for different fuel compositions

### 4.2.7 Percentage of Heat Loss through Exhaust

In an engine, not all heat energy is converted into useful work. Only a percentage is converted while the remainder are lost as heat in the exhaust. Figure 4.7 shows that Composition A has the highest heat loss and this is proven with the high exhaust temperature in Figure 4.1. Combustion using only diesel shows a lesser heat loss meaning more energy was converted into useful work.

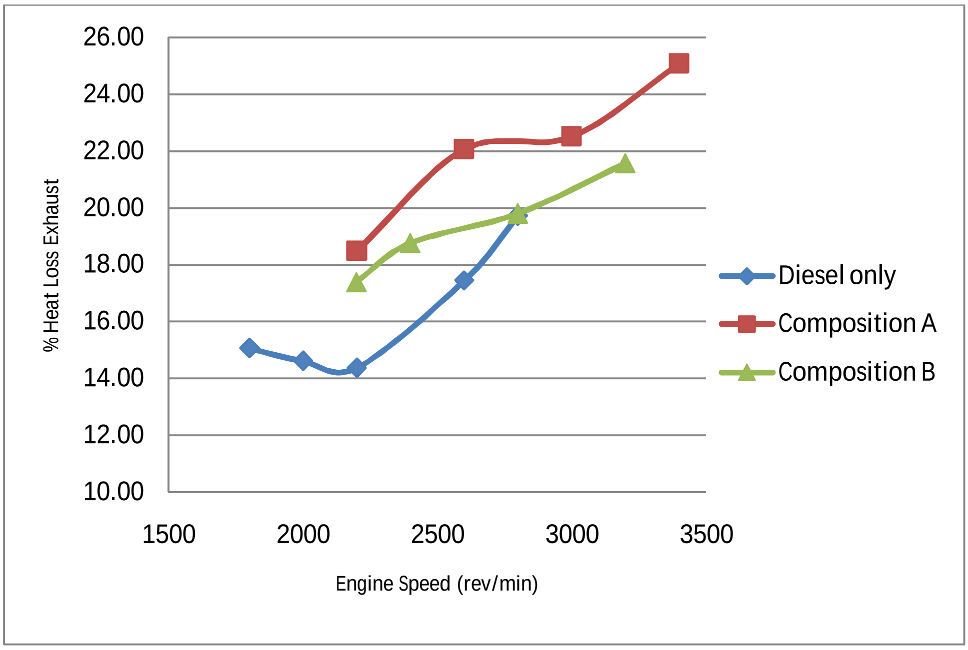


Figure 4.7: Variations of percentage heat loss through exhaust with engine speed for different fuel compositions

From the overall evaluation, combustion of Composition B shows a more positive result such as having higher power output and brake thermal efficiency as well as lower exhaust temperature. Composition B differs from the rest because it has lesser carbon dioxide. Thus, for future studies it is recommended to use syngas with a lower composition of carbon dioxide.

### 4.3 Exhaust Smoke Evaluation

Combustion of diesel produces black smoke because of incomplete combustion of the fuel. In a correctly running engine, black smoke should hardly be seen. However, during the combustion of diesel, thick black smoke was emitted from the exhaust. This shows that the engine is producing excess of carbon monoxide. During the combustion of diesel and syngas, white smoke was emitted from the exhaust as depicted in Figure 4.8. White smoke indicates that raw and unburned fuel had passed through the exhaust. Water entering combustion space also creates white smoke.


Figure 4.8: White smoke from the exhaust during the combustion of syngas and diesel

# CHAPTER 5
# CONCLUSIONS

Syngas produced from biomass gasification can be applied in various fields. In this particular study, syngas was used to run internal combustion engine specifically diesel engine. The purpose of this study is to analyze the engine performance by using imitated syngas and diesel as a fuel. Many researchers have concluded that there is a variation in composition of syngas generated from biomass gasification. This study helps to determine the appropriate composition that the gasifier should produce in order to obtain optimum power generation and engine performance. The result obtained shows that Composition B which consists of 75.7% nitrogen, 19.92% carbon dioxide, and 4.38% hydrogen, gives a high power output and brake thermal efficiency and a lower exhaust temperature while Composition A gives the opposite results. Composition A has a higher composition of carbon dioxide, thus it is recommended to use syngas with a low carbon dioxide in engine. The study has proven that using syngas in internal combustion engine does have its benefits.

## 5.1 Recommendations

For future study, it is recommended to use a lower composition of carbon dioxide in imitating syngas so as to give a more positive result. Furthermore, use a fuel flow meter to reduce the flow of diesel into the engine. This is to investigate what will happen if diesel is reduced and the syngas is increased. Since syngas consists of five gases, it is recommended that for future studies, use all five gases instead of only three gases. Using five gases will give accurate results as it depicts a more syngas characteristic.

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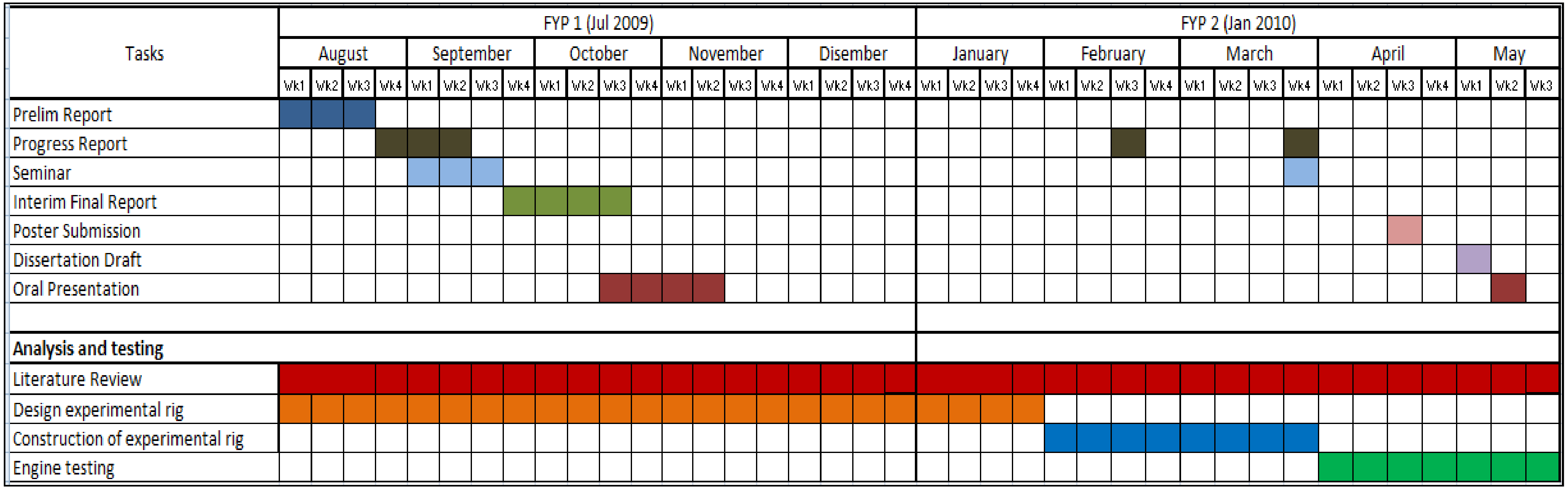
# APPENDIX A – GANTT CHART



# APPENDIX B

## Test Procedure for Engine Run

The typical procedure to run the engine and collect data is shown below.

a) The throttle or rack control is advanced to its maximum position.
b) The maximum speed of the engine is obtained.
c) The throttle or rack is kept open and slowly the needle valve is adjusted to increase the flow of water through the dynamometer until the needle valve is fully open. The engine speed is recorded.
d) The engine will be tested over the speed range just established.
e) At least five speeds are chosen between the two extremes at which to take readings of engine performance.
f) The throttle is kept open and the water flow is reduced to a trickle, so that the engine returns to its maximum speed.
g) When the engine has settled down to a steady output, the readings of speed, torque, exhaust temperature and air consumption is recorded.
h) The fuel tap beneath the pipette is operated so that the engine takes its fuel from the pipette. The consumption of 8 ml of fuel is timed. The tap is turned so that the pipette fills again. The result is recorded.
i) The temperature of the water flowing out of the dynamometer is checked to ensure it is less than 80$^{o}$C. If the temperature is higher than this, the water flow is increased to cool the dynamometer bearing seals.
j) The flow of water into the dynamometer is increased until the engine speed drops to the next highest selected value. Because the time response of the dynamometer is fairly slowly, the needle valve has to be operated slowly.
k) Before taking another set of results, allow time for the engine speed to stabilise. I
l) Step (j) is repeated until the dynamometer needle valve is fully open.