INVESTIGATION SIZE OF SOOT PARTICLE BEHAVIOUR USING BIODIESEL BY COMPUTATIONAL AND EXPERIMENTAL TECHNIQUES

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PENYELIDIKAN SAIZ PARTIKEL JELAGA DENGAN MENGGUNAKAN TEKNIK SIMULASI DAN EKSPERIMEN

Dalam enjin diesel jelaga menghasilkan akibat pembakaran bahan api yang tidak lengkap berlaku dalam kebuk pembakaran. Sesetengah jelaga ini akan bergerak ke omboh dan perlahan-lahan bergerak ke bawah di mana minyak pelincir terletak. Jelaga ini menjadikan minyak pelincir menjadi kotor dan meningkatkan kelikatan. Apabila kelikatan minyak pelincir menjadi tinggi, bermakna kekerapan menukar minyak pelincir diperlukan untuk memastikan prestasi enjin sentiasa berjalan lancar. Jelaga ini juga mempunyai zarah pepejal (Particulate Matter: PM) dan nitrogen oksida (NOx) yang sangat berbahaya kepada alam sekitar.

Tujuan projek ini adalah untuk menganalisis sifat saiz partikel jelaga di dalam enjin diesel. Selain itu, tujuan projek juga untuk membandingkan saiz zarah jelaga yang dihasilkan oleh minyak Jatropha dan minyak diesel dalam enjin diesel. Dalam eksperimen ini, minyak Jatropha dan minyak diesel akan di campurkan dan kemudian minyak ini akan di bawah ke makmal untuk ujian enjin dyno. Untuk menganalisis jelaga, penguji asap telah digunakan untuk menyiasat sifat jelaga yang datang daripada enjin diesel. Jelaga yang datang daripada ujian enjin dyno telah dikumpul dan dibawa ke makmal mikroskop imbasan elektron(SEM) untuk kajian lanjut mengenai berjelaga.

INVESTIGATION SIZE OF SOOT PARTICLE BEHAVIOUR USING BIODIESEL BY COMPUTATIONAL AND EXPERIMENTAL TECHNIQUES

In a diesel engine the soot produce as a result of incomplete fuel combustion happen in the combustion chamber. Some of this soot will move to piston and slowly move down where the lubricant oil is located. This soot makes the lubricant oil become dirty and increase its viscosity. When the lubricant oil viscosity becomes high, that mean often change of lubricant oil is needed to keep up the engine performance. This soot also has solid particles (Particulate Matter: PM) and nitrogen oxide (NOx) that is very harmful to the environment.

The purpose of this project is to analyze the properties of size soot particles inside the diesel engine. Besides that, this project purpose also to compare the size of soot particle produce by use Jatropha oil and diesel oil in diesel engines. In this experiment, Jatropha and diesel fuel was mixed and test under engine dyno. To analyze the soot, the smoke tester was used to investigate the properties of soot that comes out of the diesel engine. The soot that comes out of the engine dyno test was collected and brings to scanning electron microscope (SEM) to further study about the soot.

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CHAPTER 1

PROJECT BACKGROUND

Internal combustion engines produce soot as a result of incomplete fuel combustion. Ideally, complete combustion in a cylinder would only produce carbon dioxide and water, but no engine is completely efficient.

Because of the way that fuel is injected and ignited, soot formation occurs more commonly in diesel than in gasoline engines. Unlike gasoline engines where the fuel/air mixture is ignited with a spark, fuel and air entering the diesel cylinder ignite spontaneously from the high pressure in the combustion chamber. The fuel and air mixture in diesel engines typically does not mix as thoroughly as it does in gasoline engines. This creates fuel-dense pockets that produce soot when ignited. While the majority of soot easily escapes through the exhaust, some gets past the piston rings and ends up in the oil.

Soot produced by burning coal, diesel, and wood causes significantly more damage to the environment than previously thought, according to research published today. So-called "black carbon" could cause up to 60% of the current warming effect of carbon dioxide, according to the US researchers, making it an important target for efforts to slow global warming. Around 400,000 people are estimated to die each year due to inhaling soot particles, particularly because of indoor cooking on wood and dung stoves in developing countries. These deaths are mainly among women and children and ends up in the oil [1].

So, it is important to study about the size of soot particles in diesel engine because this particle is so harmful to the engine and environment. Much variety of step and precautions needs to be taken in order to terminate the soot from emitted to engine and environment. Beside step to terminated the soot from terminated, the step to reduce the emitted of soot also need to be consider in order to reduce the effect of this harmful soot.

Diesel engines consume a carbon-rich fossil fuel that liberates soot as a byproduct of combustion. Soot consists of micrometer-scale particles of elemental carbon. Figure 1 show the structure of soot particle:

Figure 1: Soot

Excessive soot levels in the oil can quickly overcome the dispersant additives in lower quality engine oils and ultimately form what is commonly known as sludge. As the dispersants become depleted, the soot particles clump together, attach themselves to engine surfaces, and lead to reduced lubrication due to impeded oil flow through the engine as well as through the oil filter [2].

High oil soot levels can also lead to a higher lubricant viscosity which impedes oil flow and increases engine wear. So, how is it that soot enters the crankcase to mix with the lubricant oil? As the piston goes down for every power stroke, soot can accumulate on the cylinder liners of each bore and can be scraped down by the oil control piston rings. Soot can be further delivered to the crankcase via blowby of combustion gases past the piston rings (especially worn rings). In addition, the thin motor oil film retained on the bores can partially break down under combustion heat, leaving more soot. The performance of anti-wear lubricant additives can also be negatively impacted and lead to increased wear and premature engine failure.

To make matters even worse, high soot conditions can lead to the formation of carbon deposits in the piston ring groove. This causes degradation of the oil seal between the piston rings and cylinder liner and eventually cause abrasion. As abrasion widens the gap between the rings and liner, increasing amounts of combustion byproducts such as gases and unburned fuels blow into the crankcase. Eventually, the cylinder loses more and more compression and the expanding gases from combustion increasingly lose their ability to push the piston down. This is realized by the operator as a loss in horsepower and fuel efficiency [3].

Recently, the liquid fuel is limited in the world. The increasing usage of diesel engine is the way to increase the efficiency of liquid fuel, because it has the highest thermal efficiency when compared with other internal combustion engines. In addition, using diesel engine also reduce the carbon dioxide emission which is the cause of global warming. However, the main pollutants from diesel engine are solid particles (Particulate Matter: PM) and nitrogen oxide (NOx). The pollutants should be removed from exhaust gas because they affected environment and human health such as lung cancer [4].

From the reviewed literatures, they found that the average size of primary particles was approximately 20 – 60 nm while the agglomerated size of soot was approximately 100 – 300 nm. Moreover, some soot particle was also agglomerated with ash (calcium), which included in lubricant oil.

The diesel is fossil fuel which is consumable and limited in the earth. The alternative fuels, such as biodiesel, are the good choice for usage instead of diesel fuels. The main advantages of biodiesel over diesel fuel are its very low sulfur and aromatic hydrocarbon content. In addition, it includes oxygen molecule and also acts like environmental friendly fuel. Due to environmental benefits, there has been increasing interest in utilizing biodiesel fuel in transportation. The biodiesel fuel can substantial reduce the net global warming gas (CO2). The combustion of biodiesel emits greenhouse gas to atmosphere as same as diesel fuel. However, in theoretical the net emission of carbon dioxide is zero while diesel combustion is 100 % emitted to atmosphere [5].

Due to the biodiesel is produce from biomass, as plants. The growth of plants pulls out of the atmosphere to be a carbon by photosynthesis. So the carbon dioxide emitted from bio-combustion and the carbon dioxide absorption of the bio-plants is balance, the increasing of greenhouse gas in the atmosphere can assume to be zero. The biodiesel fuel results in more complete combustion than that of diesel, because it has oxygen content in its molecule. The complete combustion of biodiesel emits less and smaller size of particulate matter than that of diesel fuel. The reduction of biodiesel particulates are approximately 38% when compared with diesel.

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The effect of soot to the engine

Soot loading in diesel engine oil can present wear problems. Diesel engines consume a carbon-rich fossil fuel that liberates soot as a by-product of combustion. Soot consists of micrometer-scale particles of elemental carbon. The existence of soot is because of signifies incomplete combustion, incorrect air fuel ratio, improper combustion temperature, insufficient residence time in the combustion zone and non-availability of sufficient oxidants. Diesel engines usually run lean with excess air for combustion. However, under acceleration conditions, much fuel is injected and there is a temporary air starvation situation in the combustion chamber as the turbocharger labors to spool up and deliver sufficient pressurized air to the intake manifold, thus yielding unburned soot [6].

Factors that Cause Excessive Soot Levels in Crankcase Oil:

1. Periods of excessive idling
2. Worn piston rings
3. Injectors with poor fuel spray patterns
4. Rich air-fuel ratios
5. Clogged air filters decreasing the air supply, which increases the fuel-air ratio and ultimately leads to increased soot formation

Soot particles are 98 percent carbon by weight and typically spherical in shape. While most are only around 0.03 microns in size, they often clump together to form larger particles. Individual soot particles pose little risk to engine parts, but clumps of soot can cause damage [7].

The soot particles clump together, attach themselves to engine surfaces and lead to reduced lubrication due to impeded oil flow through the engine as well as through the oil filter. High oil soot levels can also lead to a higher lubricant viscosity which impedes oil flow and increases engine wear. So, how is it that soot enters the crankcase to mix with the lubricant oil? As the piston goes down for every power stroke, soot can accumulate on the cylinder liners of each bore and can be scraped down by the oil control piston rings. Soot can be further delivered to the crankcase via blow by of combustion gases past the piston rings (especially worn rings). In addition, the thin motor oil film retained on the bores can partially break down under combustion heat, leaving more soot. Such soot accumulations in the engine oil have been observed in the 2% to 10% range. In concentrations starting around 3 to 5% in the engine oil, soot can become problematic for engine owners/operators [7]. High soot load conditions lead to loss of oil dispersancy as an oil dispersant additive is consumed. As dispersancy is lost, soot particles agglomerate and form larger particles that build up on engine surfaces. This soot and sludge eventually impedes oil flow, and it can also form on oil filters, blocking oil flow and allowing dirty oil into the engine. In addition, high soot levels within motor oil increase its viscosity, further impeding oil flow and increasing engine wear. Anti-wear additive performance is also affected in high soot conditions as additives are gradually removed from the oil by adsorption to soot particles, leading to increased wear and premature engine failure [8].

To make matters even worse high soot conditions can lead to the formation of carbon deposits in the piston ring groove. This causes degradation of the oil seal between the piston rings and cylinder liner and eventually causes abrasion. As abrasion (scratches or removal of surface) widens the gap between the rings and liner, increasing amounts of combustion by products such as gases and unburned fuels blow into the crankcase. Eventually, the cylinder loses more and more compression and the expanding gases from combustion increasingly lose their ability to push the piston down. This is realized by the operator as a loss in horsepower and fuel efficiency.

Diesel exhaust has been found to contain many toxic air contaminants. It is a carcinogen which causes lung cancer and is associated with bladder cancer. Among these pollutants, fine particle pollution is perhaps the most important as a cause of diesel's deleterious health effects. Diesel exhaust pollution accounts for over one quarter of the total hazardous pollution in the air, and a disproportionately high share of the load of sickness and death caused by pollution [9].

The lean-burning nature of diesel engines combined with the high temperatures and pressures of the combustion process results in significant production of nitrogen oxides, and provides a unique challenge in the reduction of these compounds. Modern on-road diesel engines typically must utilize selective catalytic reduction to meet emissions laws, as other methods such as exhaust gas recirculation cannot adequately reduce NOx to meet newer standards in many jurisdictions. However, the fine particulate matter (sometimes visible as opaque, dark-colored smoke) have traditionally been of greater concern in the realm of diesel exhaust, as they present different health concerns and are rarely produced in significant quantities by spark-ignition engines [10].

Exposures have been linked with acute short-term symptoms such as headache, dizziness, light-headedness, nausea, coughing, difficult or labored breathing, tightness of chest, and irritation of the eyes and nose and throat. Long-term exposures can lead to chronic, more serious health problems such as cardiovascular disease, cardiopulmonary disease, and lung cancer.

Ambient traffic-related air pollution was associated with decreased cognitive function in older men. Mortality from diesel soot exposure in 2001 was at least 14,400 out of the German population of 82 million, according to the official report 2352 of the Umweltbundesamt Berlin (Federal Environmental Agency of Germany) [11].

In addition to the traditional types of fuel that have been around for as long as we can all remember, such as traditional gas, petroleum and diesel, we have also had biofuel as an option over the last few years. But even more recent within the last few years is the growing availability of even more different types of biofuel that are now available. This includes biodiesel, biogas, bioalcohol and more. And a relatively new type of biofuel to enter the industry of alternative energy is Jatropha biofuel [12].

Jatropha biofuel is a derivative of a special type of plant, which essentially helps to create oil from a very simple organic, natural and renewable resource for a sustainable energy resource. When you burn Jatropha oil in a lamp, fine soot is emitted. Actually this soot is Activated Carbon, which adsorbs poisonous materials from air, cleans the air, and reduces Respiratory problems. So using jatropha oil as a biodiesel has many advantages. It is an alternative and renewable source of energy and the biodiesel is free from sulphur. Using of biodiesel reduces the pollution [12]. The amount of components present in the petroleum is reduced to half in the biodiesel. The graph in figure 4 show percentage of black smoke emitted from diesel and biodiesel oil:

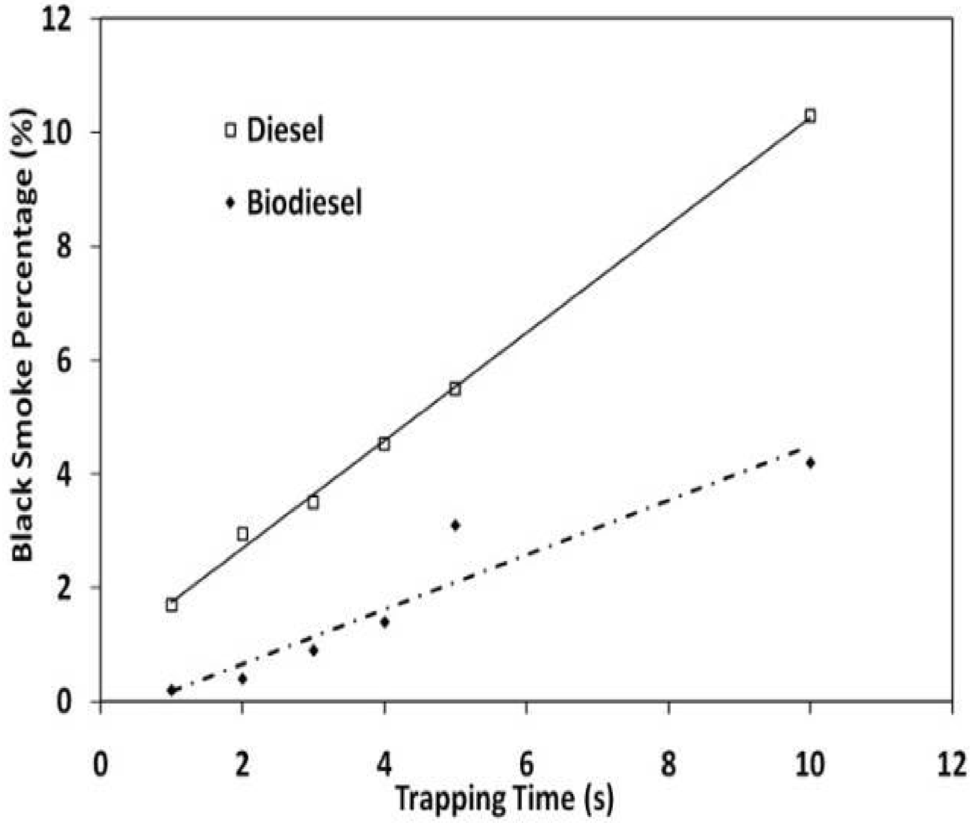


Figure 4: Percentage of black smoke emitted from diesel and biodiesel oil.

PROJECT OBJECTIVES

1. To investigate soot particle size distribution by using biodiesel:
   a. To analyze the properties of size soot particles inside the diesel engine.
   b. To compare the size of soot particle produce by use Jatropha oil and diesel oil in diesel engine.

2. To validate the soot particle size by Matlab simulation with a series of soot measurements by scanning Electron Microscope.
   a. Develop a model that shows the soot movement inside diesel engine using MATLAB software.

PROJECT SCOPES

1. Study about the size soot effect the diesel engine.

2. Study the development or the formation of soot in diesel engine.

3. Study the effect of jatropha to the engine and the size of soot that will emit.

4. Study the soot movement that develop under combustion process of a diesel engine by using MATLAB

Chapter 2

METHODOLOGY

My research methodology requires gathering relevant data about the performance of diesel engine in order to differentiate the different operation of the two engine system and the waste material that come out from the exhaust. Beside that I also have to research about the formation of soot in diesel engine and it effect to engine, environment and health. Therefore, there is 2 methods to do this research

a)Experimental

By using smoke tester in order to investigate the properties of soot that comes out from the diesel engine. Next we will bring the soot that we collect before to examine it under microscope to further study about the soot.

b) Numerical Method

Soot movement inside combustion chamber of diesel engine is investigated by using MATLAB software

2.1 Experimental

This study focuses on the formation of soot in diesel engine, the size of soot particles produce and it effect to engine, environment and health. Firstly the Jatropha oil was mixed with diesel fuel oil according to the standard proportion. This mixed oil will test with diesel engine through engine dyno tester. After that the gas analyzer and smoke tester was used in order to investigate the properties of soot that comes out from the diesel engine. Finally, the soot that collect was brings to examine it under inverted microscope to further study about the soot agglomeration size. There are 5 steps to complete this project:

I. Jatropha oil and diesel mixture

To produce B20 (Jatropha) bio-diesel the Jatropha oil need to be mix with original diesel fuel. Generally there are four type clasfication of bio-diesel that is B5, B10, B15 and finally B20. In this study we have choice B20 (Jatopha) to be chosen to run in the research. This step is to study the relationship of size soot formation using bio-fuel (Jatropha oil) and diesel fuel. This is the proportion ratios of the Jatropha oil and diesel oil that will mix up:

a) 20% - [100ml biodiesel + 400ml diesel – B20]

From the mixed up of this two fuel we will bring it to test will diesel engine. We will study the effect of each fuel and the size of soot that emitted.

II. Diesel engine-dyno and smoke tester

a) Smoke meter

Figure 1 Smoke meter tester

Diesel Smoke Meter capable of measuring smoke opacity of diesel vehicle exhaust in % Opacity & K-value with measurement of RPM & engine oil temperature.

Operation:

Firstly the diesel engine must be set at the RPM that needed. After the engine RPM reach the specification insert the nozzle of smoke meter inside the exhaust of the diesel engine. Pump

the smoke meter tester about ten times and the soot will be trapped at the filter paper. From this soot the opacity value can be measured using opacity scale.
Although gas analyzer is more efficiency to analyze soot but because of budget the smoke meter was choice to use for this project

III. Collect the soot

The apparatus that use to collect soot is filter paper. The filter paper function is to trap soot from the diesel exhaust. Next, the filter paper will put into the petri dish. The function of petri dish is to protect the filter paper that contain soot particle from mixed with air.

IV. Measure the opacity value

The opacity value that traps at the filter paper was measure using opacity scale.

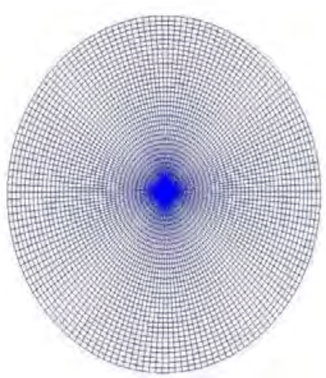
Figure 2 Opacity scale

V. Examine the properties of soot under inverted microscope

The soot that collects will be observed under the inverted microscope. The soot is compared according to it type of fuel use and related to its average soot agglomeration size. The average soot agglomeration size was get from the inverted microscope software. Firstly, the sample soot that has trap on the filter paper was examined and the picture of the sample was taken by camera. Next, the sample picture was saved in the computer software. The computer software has ruler function that enable the user to measure the diameter of sample materials by just drag the ruler across the boundary of the sample. The soot that has highest number agglomeration size pattern will be measure using the software.

2.2 Numerical Method

Based on the research of simulating the soot size in diesel engine, the distribution and soot size analysis are based on modelled using the Kiva-3v CFD simulation code. KIVA-3v CFD are based on KIVA software that predicts complex fuel and air flows as well as ignition, combustion, and pollutant-formation processes in engines. KIVA-3V uses a block-structured mesh with connectivity defined through indirect addressing. The departure from a single rectangular structure in logical space allows complex geometries to be modeled with significantly greater efficiency because large regions of deactivated cells are no longer necessary. Below show the figure of A typical cell used in Kiva3v simulation with points for trilinear interpolation and KIVA-3V block-structured mesh.



KIVA cell volume from radial angle

KIVA cell volume from top view

Figure : Both figure shows the mesh configuration of computational domain of the combustion chamber volume (Source: Thesis Wan Mahmood)

From this block-structured mesh, the computational domain represents the combustion chamber volume with the bowl-in-piston and flat head cylinder configurations. Details of the mesh configuration used in the present study are given in Table 1 and engine specifications are tabulated in Table 2. The simulation covers the closed part of the engine cycle from inlet valve closing (IVO) to EVO. In-cylinder pressure, heat release rate, soot and NOx concentration were used for calibration purposed.

Table 3.0: Specifications of the mesh configuration

Parameters		Mesh configuration
Total number of cells		201,900
Number of cells	Azimuthal	150
	Radial	37 (20 in bowl region)
	Axial	39 (15 in bowl region)
Resolution	Azimuthal (°)	2.4°
	Radial (mm)	0.83 – 1.15
	Axial (mm)	0.99 – 3.63

Table 3.1: Specifications of the Diesel Engine

Parameters	Specifications
Engine Type	4 valve DI diesel
Bore × Stroke	86.0 × 86.0 mm
Squish height	1.297140330 mm
Compression Ratio	18.2:1
Displacement	500 cm^3
Piston Geometry	Bowl-in-piston

2.2.1 SOOT PARTICLE TRACKING APPROACH

Fig. 12 shows cumulative mass of soot (formed, oxidised and net) in the combustion chamber as a function of crank angle (CA) degree obtained from Kiva3v simulation. The peak of the net soot profile is located at around 35° CA after top-dead centre (ATDC) suggesting that the phenomenon of soot formation dominates until this point. According to Dec's observations from his optical studies, soot particles continue to nucleate until the end of injection in the upstream region of fuel jet and grow in size as they move to the downstream region. However, the present investigation considers mass-less soot particles where smaller nucleated particles and bigger particles due to surface growth are not differentiated and they have been tracked from three crank angle instants where soot formation process is a dominant process. Soot particle paths have been investigated considering three successive starting instants, which are, first, the point where a reasonable amount of soot is formed in the combustion chamber, i.e. 8° CA ATDC (halfway through the injection period), second, the point where injection is already completed and soot formation process is dominating, at 18° CA ATDC, and finally, the point where oxidation process begins to overcome the formation process, which around 35° CA ATDC.

To simulate the soot distribution and transport, trajectories of an individual or a parcel of soot particles are tracked through the flow field using a Lagrangian approach. Locations of the soot particles at each time step are not discrete and can be anywhere in the domain. However, the velocity vector is discrete and is known only at the cells nodes. It is therefore necessary to evaluate the velocity vector at the particle position. For this purpose, an Radial Basis Function interpolation technique was used. Soot particles that hit the walls especially the ones from inside the fuel jet are assumed to be deposited onto the bowl walls and oxidized.

2.2.2 MATLAB SIMULATION ANALYSIS

To detect the soot movement inside the combustion chamber, the first position of soot particle need to determine first. It can be determine by the result from the distribution of soot at different crank angle as mention by CFD Kiva-3v that have been done by Wan Mahmood (2008) as shown in appendix A. Based on appendix A, it shows the percentage of soot particle at different region. The darker region shows the higher concentration of soot, compared with lighter region shows lower concentration of soot particle.

The data from CFD Kiva-3V, will be included into the MATLAB routine to calculate in determining the position soot particle. MATLAB routine is used to calculate the position of soot particle inside the combustion chamber. The result of the simulation will be in tabulated form which represents the data of each cell inside the combustion chamber. The data of the simulation will be copied into excel to plot the graph which represent the result of soot movement inside the combustion chamber in radial angle and axial angle view. The first step to run the simulation is by choosing the suitable crank angle. For this research, the crank angle chosen are 4˚, 8˚ and 30˚. The value of rho, θ and z is inserted as being asked by the program. For each crank angle, there are three type of analysis that has been done; which are rho manipulated, theta manipulated and z position manipulated. Apart from that, in each of analysis there will be four types of soot diameter are chosen; 300nm, 5000nm, 30000nm and 40000nm. The analysis of data is done by comparing the result for each crank angle and from this point the behavior of soot movement can be discussed.

Chapter 3

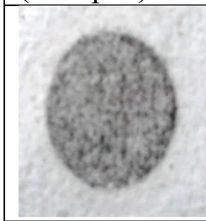
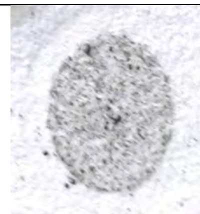
RESULT AND DISCUSSION

Experimental

Table2: Sample of soot opacity

Type of oil	rpm	Load	Opacity
B20 (Jatropha)	2500	2	5
		4	6
		6	6
		8	7
		10	8
		12	8
Diesel	2500	2	6
		4	7
		6	7
		8	8
		10	9
		12	9
Palm oil	2500	2	4
		6	5
		10	6

Table 3 Sample of soot at filter paper

Rpm:2500, Load:10		
B20 (Jatropha)	Palm oil	Diesel oil
		

From this project the result shows that the biodiesel oil is more environmental friendly compare to diesel oil. This can be proving by compare the opacity value at the 2500 rpm which are the maximum rpm value of biodiesel and diesel oil emissions at table 2 and table 3. The opacity value of B20 (Jatropha) and Palm oil is clearly lower compare to diesel oil. The highest opacity value of B20 (Jatropha) is only 8 while the highest value opacity for Palm oil is only 6. The highest value of Diesel oil opacity is 9 that is the maximum opacity value in the opacity value.

Table 4: Soot properties at 2500 rpm and at load 2(minimum load) under inverted microscope

Oil	Average soot agglomeration size
Diesel	0.04mm
B20(Jatropha)	0.03mm
Palm oil	0.01mm

Table 5: Soot properties at 2500 rpm and at load 12(maximum load) under inverted microscope

Oil	Average soot agglomeration size
Diesel	0.05mm
B20(Jatropha)	0.04mm
Palm oil	0.02mm

From analysis at maximum load and minimum load the Diesel oil average soot agglomeration size is the biggest size with 0.05mm in size as shown in Table 4 and Table 5. Secondly, was B20 (Jatropha) with 0.04mm in size and finally was the Palm oil with 0.02mm in size. The average soot agglomeration size is bigger than biodiesel because the lower concentration of biodiesel particle, which is readily oxidized with more available oxygen, in combustion flame due to oxygenated biodiesel fuel. The oxygen content in fuel has a strongly influence on the soot particle, emitted from combustion. Consequently, using the biodiesel instead of diesel can reduce the net global warming gas, emitted to atmosphere. Besides that, the biodiesel combustion also decreases accumulate particle size thus reduces the concentration of particulate, emitted from the exhaust pipe.

Numerical Method

Based on the result from MATLAB routine, the result shown the movement of soot particle within different size of soot particle which are; 300nm, 5000nm, 30000nm and 40000nm. As mentioned before, the result as shown in this result part will be divided into two parts which are radial part (front view) and axial part (side view).

Based on the result, for all crank angle simulation data, the data shows when diameter of soot is increase, the chances of the soot to be closed with the wall of the combustion chamber are lower. This result is shown in figure 4 for CA 8˚.

Rho=1.8cm, θ=25º and z=8.8cm

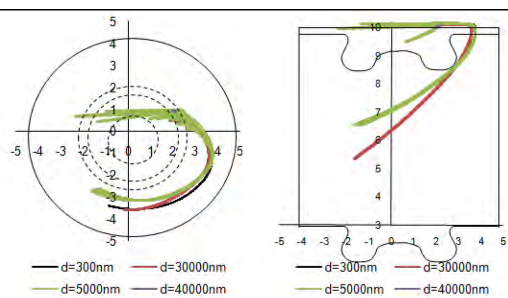


Figure 4 Soot movement when CA 8˚, rho=1.8cm, θ=25˚ and z=8.8cm