Chapter 7

Biodiesel for Gas Turbine Application — An Atomization Characteristics Study

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Additional information is available at the end of the chapter

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1. Introduction

Fossil fuel has been the primary source of fuel ever since it was discovered and comes in the form of coal, petroleum and natural gas. Discovery of fossil fuel dates back to prehistoric time where caveman discovered how to burn coal for heat source. Coal which is also part of fossil fuel and is developed over millions of years can even extend up to 650 million years. With excessive usage of fossil fuel as source of energy, amount of fossil fuel around the world is declining at a rapid rate. With petroleum being the main source of fuel in automotive industry and power generation, this lead to price hike globally with the fastest depletion rate. Experts forecast that complete depletion of petroleum in the world is expected to happen in between 50 to 80 years depending on the consumption.

In advance, the global fuel crisis in the 1970s triggered awareness amongst many countries of their vulnerability to oil embargoes and shortages. In addition, the rising world crude oil is another primary concern for developing countries because it increases their import bills. The world is presently confronted with the twin crisis of fossil fuel depletion and environmental degradation. Fossil fuels have limited supply and the increasing cost of these fuels has led to the search of renewable fuels to ensure energy security and environmental protection. With increased interest in emissions and reduction of fossil fuels, considerable attention was focused on the development of alternative resources, in particularly biodiesel fuels.

Even more, the effect of global warming is largely felt due to the greenhouse gas emission and power producing plants contribute a major involvement in this aspect. Replacing fossil fuel with renewable energy is one of the main solution. Biodiesel is a renewable, biodegradable and oxygenous fuel with almost similar physical and chemical characteristic to diesel [1]. Biodiesel are ethylic or methyl esters of acids with long chain derived from vegetable oils and animal fats through a thermochemical process involving the transesterification process [2]. In addition, biodiesel being an oxygenated fuel whereby it is environmentally cleaner than diesel with respect to unburnt hydrocarbon (UHC) and particulate matter (PM) emissions [3]. The success of biodiesel is proven as can be seen in its use as a secondary fuel for vehicle in Europe and followed by other developed countries. The reason for using biodiesel, is that it can increase engine performance and produces low emission compared with conventional diesel fuel [2,5,6,17]. Biodiesel can be obtained from various sources such as palm oil [7], rapessed oil [14-15], soybean oil [8,14-15], vegetable oil [9-10], waste cooking oil [11-12], oleaginous microorganisms [13] and sunflower seed oil [14-15]. An important effect that has to take into consideration is the fuel spray atomizer whereby it is the contributing factor that will affect the efficiency and performance of power generation. Spray tip penetration and mean droplet size of which are the atomization characteristics of biodiesel fuel play an important role in the emission characteristics and the engine performance [26]. Biodiesel is mostly applied in transportation like petroleum diesel. Biodiesel blended fuel can be used as fuels for diesel engines without any modification. Moreover, pure biodiesel can be used as well but with some minor modification. Biodiesel gives better lubrication compared to diesel fuel [27-28]. Biodiesel also provides advantages on performance, engine wear, value for money and availability.

Despite the significant advance arising from definition of the regulatory milestone, there are still many issues relating to the production and use of biodiesel that need to be debated. Among the issues, the ones that stand out are those of a technical order, such as how the biodiesel specifications and its consequences for the performance, emissions and durability of the engine and its system. Therefore, further research on ideal atomization characteristics of biodiesel fuels should be carried on for progressive development of this potential source in combustion engineering. Various biodiesel blended fuel derived from waste cooking oil (WCO) are produced through the method of transesterification. ASTM standards are used to identify and verify physical and chemical properties such as viscosity, density, flash point and cetane number of the biodiesel produced. Meanwhile, a fuel atomizer designed act as a device that convert the working fuel flow into a finely dispersed flow of fuel droplets in the form of a spray. Fuel spray testing will determine atomization characteristics such as Sauter Mean Diameter (SMD), spray angle, spray width, spray length and spray tip penetration for different types of fuel under certain atomization conditions. Thereafter, a computer simulation using CFD Fluent software is used to compare the experimental results to ascertain the appropriate biodiesel blend to be applied in the microturbine and gas turbine combustion system.

This project is to study the possible application of diesel and biodiesel blends in gas turbine and microturbine application. Research of this project involves testing several compositions of diesel and biodiesel blends. The produced diesel and biodiesel blends will be tested to understand the behavior and atomization characteristics such as spray tip penetration, spray cone angle, spray width and Sauter Mean Diamater (SMD). Generally, biodiesel has larger spray tip penetration and Sauter Mean Diameter while smaller spray cone angle and spray width compared to diesel. Five sample of fuels will be tested which are B20, B50, B80, B100 and D100. The alphabet B represents biodiesel and the number that follows represents the percentage of the fuel that is made up of biodiesel. For example, B80 simply means biodiesel blend that is made up of 80 % biodiesel and 20 % diesel. Research conducted on biodiesel shows that using biodiesel rather than conventional diesel reduces carbon dioxide pollutants into the environment. Using full 100 % biodiesel (B100) eliminates all sulphur emissions, removes carbon monoxide pollutant and reduces hydrocarbon pollutant by 75 % to 90 % compared to conventional diesel. This means greenhouse gasses can be significantly reduced if B100 is used because this fuel has no emissions of carbon dioxide [32]. Palm oil will be derived through transesterification process to produce biodiesel and palm oil is easily obtained in Malaysia. Moreover, the price of palm oil will be much cheaper compared with the other resources. Palm oil quality is cleaner and good compared with other fuel. In short, biodiesel will be the most suitable fuel replacement for power generation and have more advantage environmental wise. Biodiesel can be used with the existing gas turbine power generation and only a little or no modification has to be made. It is based on the existing concept and idea in diesel engine that had been applied. Further analysis and consideration have to be taken in future to ensure that biodiesel can operate in the gas turbine without any problem

2. Research methodology

2.1. Fuel properties

The production of biodiesel was completed by conducting transesterification of Waste Cooking Oil (WCO). Relevant method was selected in this project based on its economic factors to produce different biodiesel blended fuels. Biodiesel and diesel blends of B100, B80, B50 and B20 and D100 were obtained through conducting tests that meet the requirements of ASTM D6751, Specification for Biodiesel Fuel Blend Stock for Distillate and ASTM D2880 Standard Specification for Gas Turbine Fuel Oil. This is to ensure that the produced biodiesel blended fuels meet the minimum fuel properties standards. Table 1 shows the main fuel properties that were studied with respect to its effects on atomization. Transesterification is the simplest way whereby it uses alcohol (e.g. methanol or ethanol) in the presence of a catalyst such as sodium hydroxide or potassium hydroxide, to chemically break the molecule of the raw material into methyl or ethyl esters of the renewable oil with glycerol as by-product. The chemical reaction of transesterification is ethyl esters of fatty acids plus glycerol equal to triglyceride (animals and plants fats and oil). The triglyceride will have chemical reaction with alcohol that usually is methanol or ethanol with the presence of a catalyst to produce ethyl ester and crude glycerol.

Fuel Blend	Method								
	ASTM D445	ASTM D4052	ASTM D482	ICP-OES	ASTM D4294	ASTM D1796	ASTM D5291	ASTM D5291	ASTM D5291
	Mixture Viscosity @ 40 Celcius (m^2/s)	Fuel Density (kg/m^3)	Ash Content %wt	Sodium mg/kg	Sulphur Content %wt	Water & Sediment %volume	Carbon % wt	Hydrogen % wt	Nitrogen % wt
Diesel	3.88×10^{-6}	842	0.004	0.15	0.241	0	85.37	13.27	0.14
B20	4.16×10^{-6}	847	0.004	0.8	0.106	0.03	82.24	13.16	0.12
B50	4.28×10^{-6}	855	0.004	0.8	0.063	0.05	81.33	13.01	0.11
B80	4.60×10^{-6}	865	0.005	0.9	0.026	0.08	77.79	12.56	0.10
B100	4.76×10^{-6}	872	0.006	0.8	0.003	0.1278	76.05	12.72	0.08

Table 1. Important fuel characteristics of Biodiesel and its blend with Diesel.

2.2. Atomization

Atomization is the breakup of bulk liquid jets into small droplets using an atomizer or spray [3]. Adequate atomization enhances mixing and complete combustion in a direct injection (DI) engine and therefore it is an important factor in engine emission and efficiency. This applies to microturbines and gas turbines as well as witnessed in the need for an atomizer in gas turbines when diesel is being used. Feasibility of biodiesel as a renewable fossil fuel replacement for power generation, must also consider emissions of pollutants including oxides of nitrogen (NOx), oxides of sulfur (SOx), carbon monoxide (CO), and particulate. This is true for both emergency (backup) power and base load applications. Fuel stability still remains an issue during storage, a hurdle which must be overcome in order to maintain fuel quality. Combustion systems for environmentally preferred alternative fuels like biodiesel have yet to be fully optimized for emissions. As a result, the feasibility of biodiesel as a low emission alternative fuel option is still being evaluated [33].

The atomization of fuel is crucial in the combustion and emission on engine but the atomization process in engine and in microturbine are completely different. Both microturbine and diesel engine have the same fundamentals where both operate through combustion but the principle of the atomization process in the both cases varies because the fuel injector for microturbine and diesel engine are not similar. For microturbine the combustion is continuous, so the fuel atomization in microturbine is continuous without any cycles or strokes. Atomization plays major role in combustion and emission in microturbine. By modifying the atomization process, the gas turbine can produce lower emission of nitrogen oxide (NOx) and carbon monoxide (CO). Adequate atomization enhances mixing and complete combustion in a direct injection gas turbine and therefore it is an important factor in gas turbine emission and efficiency. Otherwise, the properties of a liquid fuel that affect atomization in a gas turbine are viscosity, density and surface tension. For a gas turbine biodiesel injector at fixed operating condition,

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the use of fuel with higher viscosity delays atomization by suppressing the instabilities required for the fuel jet to break up. An increase in fuel density adversely affects atomization whereby higher fuel surface tension opposes the formation of droplets from the liquid fuel and some researchers analysis show that less viscosity of biodiesel is good to improve fuel atomization. The analysis showed the contributions to the change or rather the increase in SMD by the kinematic viscosity, surface tension and density were 89.1%, 10.7%, and 0.2% respectively and by reducing the viscosity of biodiesel this will reduce usage of petroleum diesel. However, further research need to be conducted to achieve the optimum blend in terms of cost, environmental effect and availability. A brief commentary is provided on the principal influences of fuel properties on atomization quality and injector performance. The viscosity of the fuel, on the other hand is of great importance in controlling both the formation of the continuous film immediately after exit from the nozzle and of the subsequent ligament disruption into individual droplets. The viscous forces decrease the rate of breaking-up of distortions in the liquid and decrease the rate of disruption of the droplets formed initially and increase the final droplet size. Experiment may show that both droplet diameter and penetration are directly related to fuel viscosity. An increase in fuel viscosity will also tend to increase spray penetration with heavier and more viscous fuels, the jet will not be so well atomized for a given injection pressure and the spray will be more compact. Consequently there will be a decrease in spray cone angle and in spray distribution/uniformity. The temperature relationships for kinematic viscosity shows that vegetable oils have viscosities higher than that of conventional gas oil (diesel) thus tending to produce larger droplets. Viscosity has by far the greatest effect on jet atomization with high viscosity fuels provoking deterioration in the quality of atomization. Of the relevant fuel properties, density is generally found to have relatively little influence on spray formation. Moreover, looking at the temperature relationships for relative density, the variation in specific gravity is also not appreciable. An increase in fuel density will have a small direct effect on spray compactness and penetration. Surface tension also has a direct effect on drop size but shows much less variation with temperature. Surface tension forces tend to oppose the formation of distortion or irregularity on the surface of the continuous jet and so delay the formation of ligaments and the disintegration of the jet. Hence, an increase in the liquid surface tension will generally cause deterioration in atomization quality.

The most important component in the atomization testing is an injector nozzle. An atomizer nozzle produces a fine spray of a liquid based on the venturi effect. When a gas is blown through a constriction it speed up, this will reduce the pressure at the narrowest point. The reduced pressure sucks up a liquid through a narrow tube into the flow where it boils in the low pressure and form thousands of small droplets. These theories apply to the experiment where the atomizer turns the fuel into thousands of small droplets. Besides producing fine droplets the atomizer is important for air fuel mixing. The function of air fuel mixing of an atomizer is important where a proper air fuel mixing of fuel atomization can increase the fuel combustion efficiency in the microturbine. In the microturbine there are three liquid fuel injectors, each housing a plain-jet air blast atomizer which is air-assisted with four orifices to introduce the combustion of air and a helical swirled to inject the fuel air mixture in a staged approach to facilitate engine turndown [33]. Figure 1 show the sample of fuel and air interact in a complex manner for the length of the premixed. The fuel spray is injected adjacent to the combustion air in a confined area. The presence of the preheated combustion and swirling air is critical in promoting droplet evaporation and minimizing fuel impingement on the injector walls. Combustion occurs a short distance downstream of the exit of the fuel injectors. Each of the three injectors is inserted into bellows circumferentially around the combustor on the same plane of the cross section as the right side of figure below. The empty bellow on the right houses the igniters and the circular combustion flow phenomena with sites of ignition identified is also represented in Figure 1 [1].

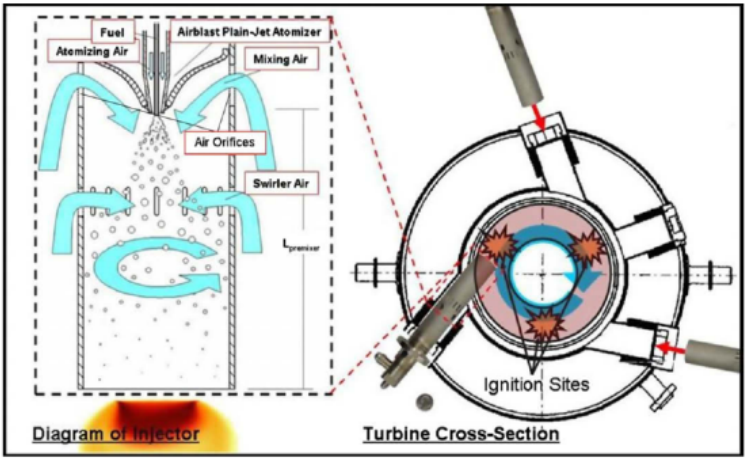

Figure 1. Air blast spray phenomena (left) and planar cross-sectional of injector configuration and combustor flow in engine (right)

2.3. Application of biodiesel in gas turbine

A gas turbine comprise of an upstream rotating compressor coupled to a downstream turbine and a combustion chamber in between. The structure of fuel sprays in gas turbine combustors is complex and varies both temporary and spatially. Slight imperfections to the fuel nozzle lip can yield significant variations in fuel spray pattern. Non uniform spray patterns can result in poor mixing between fuel and air which lowers combustion efficiency and increases emitted pollutants. The actual conditions of spray injection, dispersion, vaporization and burning of the fuel with different stoichiometric proportions of air in a well mixed environment affect the combustion stability and efficiency and pollutants formation. Specifically fuel/air mixing and the time temperature dwell history of fuel droplets determine the quality of combustion and the levels of emissions generated. However, most systems are not well mixed and require controlled mixing which in turn affects combustion and emission characteristics. Furthermore, efficiency of the gas turbine itself plays a role to control the combustion and emission characteristic. Basically, gas turbine engine applied in two major sectors which are aircraft propulsion

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and electric power plant. Implementation of gas turbine since 19th century had been commercialized and developed year by year until now. At the early stage or beginning stage of gas turbine, efficiency of gas turbine is just around 17 percent due to its low compressor, turbine efficiency and low turbine inlet temperature. There are some developments that had been made to improve operation of gas turbine such as increasing the efficiency of turbomachinery component, modification to the basic cycle and increasing the temperature of turbine inlet. The advantage for choosing the gas turbine is that it can produce greater power for a given size, high reliability, weight, long life and convenient operation compared with steam turbine. It also gives an advantage for operation part. For example, gas turbine can reduce the engine start up from few hours (steam turbine) to just a few minutes (gas turbine) to start up engine/start up turbine. Thus, gas turbine is more efficient and it can cut cost and time. Nowadays, fuel used to operate the gas turbine is diesel or natural gas whereby the efficiency and emission have to be improved even though the carbon capture had been used to reduce the release of CO_2 to the air. In advance, new approach will be implemented in gas turbine fuel by replacing it with biodiesel fuel for combustion process. Therefore, biodiesel is a good option to be used as fuel in gas turbine because it is renewable and it can sustain for long term. Even though, biodiesel is not implemented in any of gas turbine for power plant but the similarity of diesel engine and gas turbine convince that gas turbine will be more efficient using biodiesel as a fuel for power generation due to biodiesel chemical properties [1,3]. Moreover, application of biodiesel as a fuel for diesel engine proved that diesel engine can work efficiently and produce less harmful emission [27-28].The simple actual flow operation is in gas turbine shown in Figure 2 [7].There are some study had been made by other researchers to study the feasibility of biodiesel in gas turbine application and a gas turbine is also called a combustion turbine, which is a type of internal combustion engine. In recent years, studies of atomization in gas turbines were performed to study the feasibility of using biodiesel in gas turbines application. Many studies were conducted by researchers from all over world.

Atomization is a process where liquid fuel is forced through a nozzle under high pressure to form small particles in the form of spray. Atomization is highly dependent on the injection which includes the nozzle opening and also injection pressure. Studies were also performed on optimization of nozzle in order to produce well atomized fuel sprays. From atomization, various spray characteristics such as spray tip penetration, spray cone angle, spray width and Sauter Mean Diameter (SMD) can be studied. Over the years, atomization of various liquid fuels has been studied to evaluate fuel performance relationship with engine efficiency and pollutant emissions [37]. Studies of atomization performed is highly dependent on visual systems such as the Phase Doppler Particle Analyzer (PDPA). Viscosity that varies between fuels affects the atomization of various liquid fuels. To study the feasibility of biodiesel in gas turbine, sample biodiesel fuel used is jatropha oil and studies shows that jatropha biodiesel blend can be used as alternative fuel for gas turbine application. This oil has characteristics properties almost similar with diesel but need to undergo degumming or etherification to form its biodiesel fuel due to high viscosity. Another study was done on operation of a 30 kW gas turbine using biodiesel as primary fuel. The result were then compared with using diesel fuel distillate #2 and shows that biodiesel's fluid properties results in inferior atomization compared to diesel [33]. Flame structure in a gas turbine varies from that in a diesel engine. In

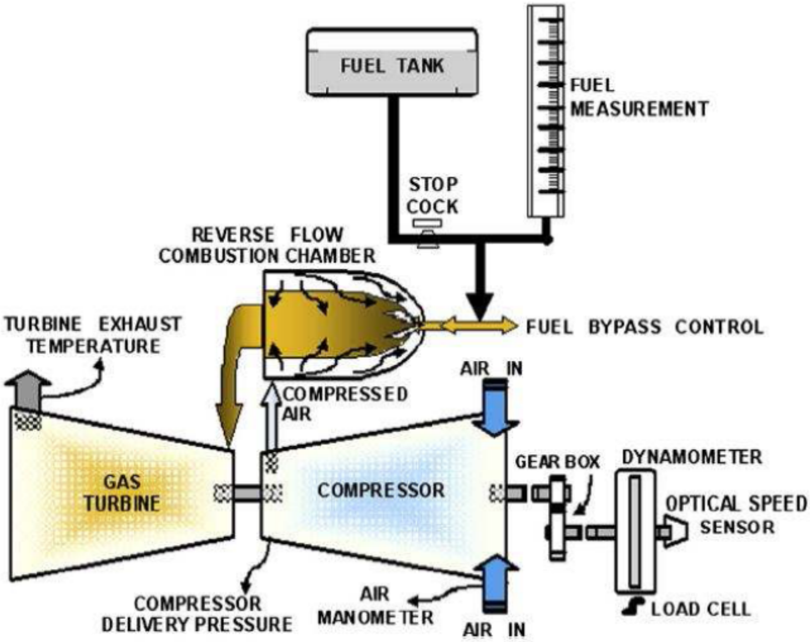

Figure 2. Simple actual flow in gas turbine

diesel engine, the flame is intermittent non-premixed reaction while the flame in gas turbine is more lean and premixed reaction. The study done on this gas turbine shows that biodiesel can be used for operation [33]. The structure of a gas turbine with injectors are placed at designated location. Fuel spray is injected adjacent to the combustion air in a confined area. The presence of the preheated combustion and swirling air is critical in promoting droplet evaporation and minimizing fuel impingement on the injector walls.

2.4. Atomization test rig

The atomization test rig was designed to achieve the atomization characteristics spray of biodiesel and diesel blends. The equipment comprise of a compressor, a timing control panel, pressure tank, solenoid valve, spray gun, test rig, and a high speed camera. Figure 3 shows the schematic diagram of the test rig. The fuel is injected into the atomizer under pressurized conditions channeled through the air compressor. An air-assist automatic spray gun connected to a high pressure pump or solenoid valve is used to atomize the fuel, using different tip size to achieve the desired atomization and spray pattern size. As the droplets are sprayed, the high speed camera is used to capture the images of the spray pattern. The atomization test was conducted for five blends of biodiesel and diesel fuel, under various pressure ranging from 0.1MPa to 0.5MPa.

2.5. CFD simulation

In order to simulate the atomization process, the Computational Fluid Dynamics (CFD) model has to be constructed. The CFD model will be simulating the spray region of the fuel atomization. Figure 4 shows a sample of simulated CFD model with square shape of the spray region using CFD preprocessor tools and Figure 5 is the axis symmetry constructed using the cylindrical shape of spray region. Both figures become the samples of the CFD model geometry simulating on spray region. Study in atomization and spray characteristic give an idea where the meshs of the atomization spray region can be created as cylinder shape or square shape [21]. Figure 4 is the computational grid for the numerical analysis and it also shows the size of the grid as modeled for atomizer [8,21]. Furthermore, different injection pressure will affect the spray length and angle. Figure 5 show the measuring points for analyzing the atomization characteristic and the calculation meshes. [8,21].

Chemical properties and ambient pressure will affect the pattern and SMD of the spray. It is proved in Figure 6 and Figure 7 whereby after the injection the velocity increased due to droplet [34]. Thus, it is a high velocity and the relative velocity of droplets injected at later stage is decreased. Pressure and temperature can also affect the spray flow. In addition, chemical characteristics also will affect the spray length, spray angle, spray pattern and SMD. It depends on the various blend of the fuel whereby every blend of fuel consist of different amount of chemical characteristic such as density, viscosity, surface tension and others. Figure 6 shows the effect of pressure and Figure 7 shows the ambient pressure with different blend of fuel.

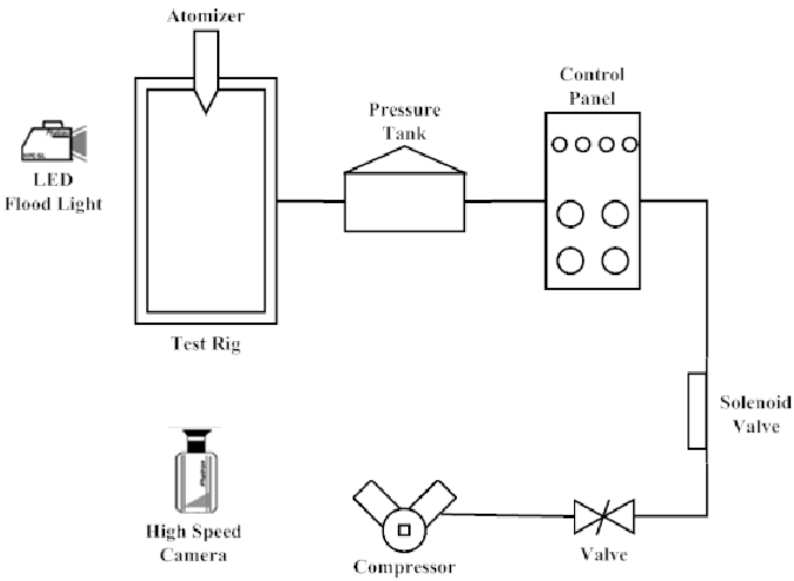

Figure 3. Experimental testing set up

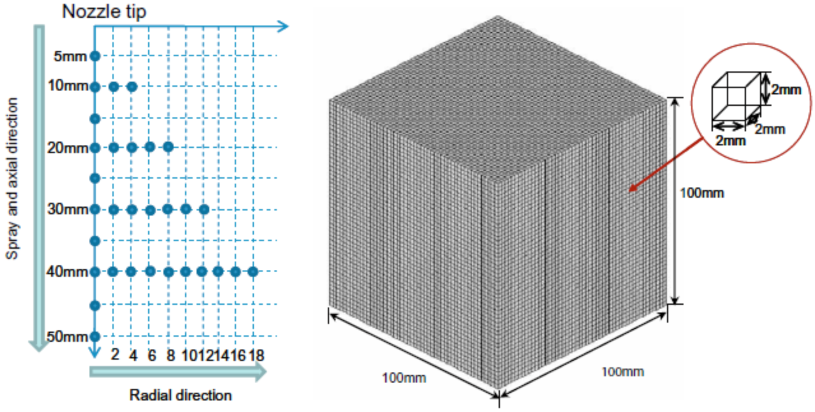

Figure 4. Measuring points for analyzing the atomization characteristics

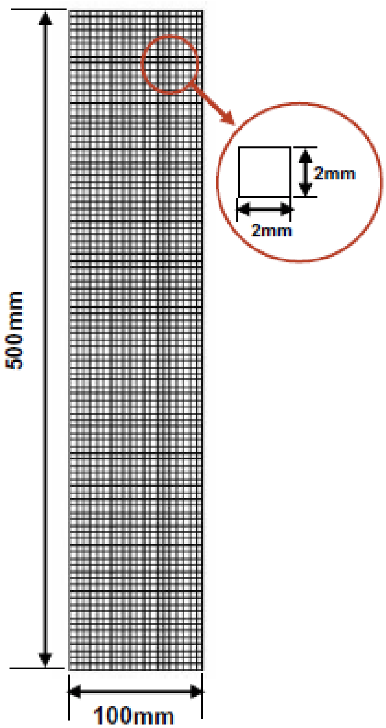

Figure 5. Computational grid for the numerical analysis

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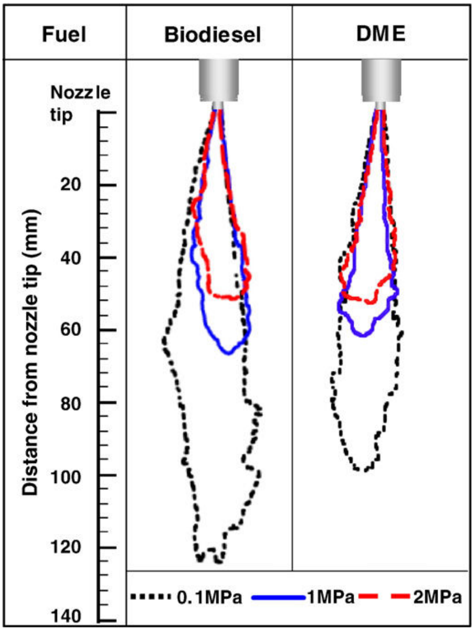

Figure 6. Spray length and spray pattern for different injection pressure

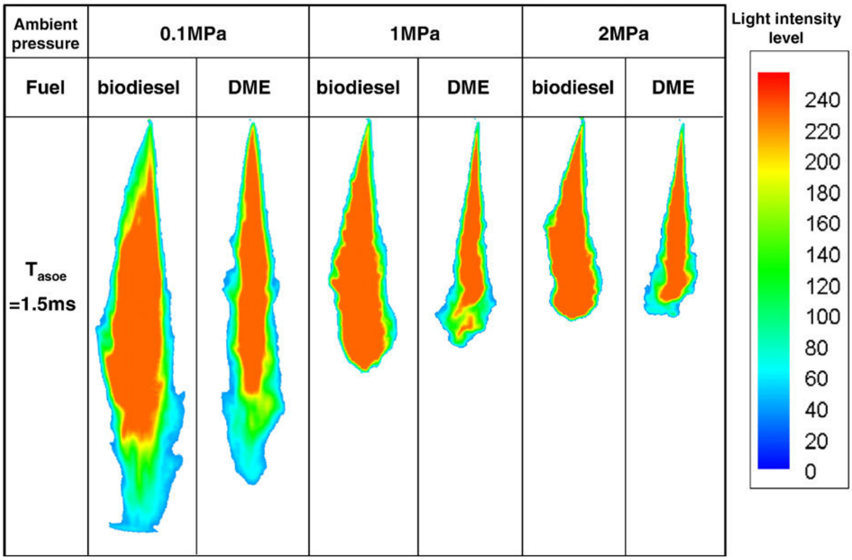

Figure 7. The contour plot of biodiesel and DME fuels at various ambient pressures

Commercial ANSYS CFD software which consists of Gambit software creates the geometry and Fluent software which solve and run the simulation of the model analysis. The CFD model was created using the specification of the real equipment used for the atomization testing experiment. It needs to be created for the atomization testing where the spray injector will produce fuel atomization in the spray region. The specification needed to create the CFD model in Gambit are the spray tip diameter and spray region of the fuel atomization. The spray tip diameter is to be 0.04 mm according to the real atomization testing equipment. Meanwhile geometry is set to be 0.5m in height and 0.5m in diameter. The smaller region of CFD model is already sufficient to generate the fuel atomization and it is much easier for the Fluent software to analyze the simulation. The CFD model was created as a cylindrical spray region with a spray tip.

The CFD model of the spray region created will only be 1/12 of the spray region. This means 30 degree of the spray region will be created. The reason behind partial creation of the spray region as the CFD model is because the spray region can be simulated and analyzed due to the smaller size and this option uses the periodicity function in Fluent software to stitch the CFD model of 30 degree spray region to be 360 degree full CFD model spray region. The construction of the CFD model in Gambit software is to create the spray region CFD model and insert meshes to the CFD model. Before generating the meshes and the CFD model, there are two ways which is constructing the CFD model directly, creating a face or volume of the desired shape and generate a mesh on it. The other way is creating vertices (vertex in the software) and create edges by joining the vertices together. By connecting the edges, this will create faces which will then create a volume after combining all the faces together. In this process of constructing the CFD model, both steps can be used and another function was used to create the CFD model is by subtracting and uniting the volume to obtain the desired shapes of the CFD model. Table 2 show the boundary conditions that had been made and the set to the interior defined as a plane that can be considered as invisible or a plane that will not cause any blockage to the fluid flow.

In advance, setting of simulation is the most important part that have to be focused to obtain good results. Experiment result will be compared with simulation results in terms of spray angle and spray pattern for all five types of fuel. In addition, experiment results are mainly photographs of the spray angle and spray pattern but in CFD simulation, the results of SMD, spray angle and spray pattern are measured directly from simulation figures. Geometry of the spray was modeled and selected boundary condition and meshing was conducted in Gambit. Furthermore, there are few assumptions that were made such as nozzle diameter and region of the spray. Figure 8 shows the Gambit model and Table 2 shows the boundary conditions. Meanwhile, Gambit file will be exported to Fluent for simulation and injection model in Fluent is surface injection and the breakup model used is k-Epsilon model. The computations were limited to only the spray nozzle to reduce converge time. Figure 9 shows domain of the spray. When everything is already set up, the simulation will begin by running the Fluent software and Figure 18 shows the atomization process.

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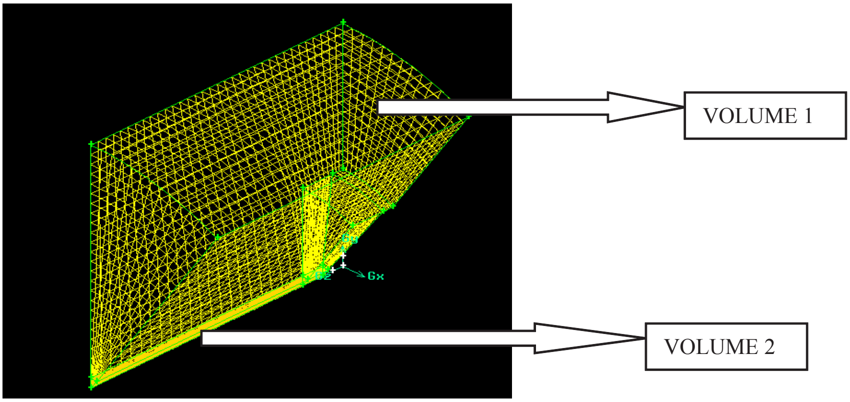

Figure 8. Geometry of atomizer

The construction of the CFD model using Gambit software whereby it is used to construct the geometry as desired. Therefore, construction of the CFD model in Gambit software is to create the spray region CFD model and insert meshes to the CFD model. Mesh can be generated on the faces or volume. The CFD model can be meshed according to the mesh element, mesh type and interval size as desired. Mesh can also be meshed by edge, face and volume. Mesh size can be set whether to create a large or small mesh element and the more meshing on the geometry the more accurate the simulation. Basically, the CFD model is divided into two volumes. The upper volume was meshed using larger interval size and the lower volume was meshed using smaller interval size. It is because the lower volume of the CFD model need more detailed CFD analysis as more droplets exists at the lower volume of the CFD model. In this project volume 1 was defined as upper volume and volume 2 is lower volume. Volume 1 and Volume 2 share the same elements and type which is Tet/Hybrid elements and TGrid type. The difference is just on the interval size whereby Volume 1 use interval size of 1 and Volume 2 uses interval size of 0.1 which is smaller interval compared to Volume 1. The reason for choosing the small interval size for Volume 2 is the fluid flow or fuel flow will go through the Volume 2 whereby the atomization process will begin. In addition, the smaller the mesh size, the more accurate the simulation and after the entire meshed step is completed, the meshed CFD model is shown as the following Figure 8 and the settings that had been made are shown in Table 3.

After the geometry is meshed, the geometry must be defined with boundary conditions. Then, the mesh file can be exported to the Fluent software. Table 2 shows the name and types of the boundary conditions. The set of interior is to be defined as a plane that can be considered as invisible or a plane that will not cause any blockage to the fluid flow. If the boundary is not properly defined, it will be automatically defined by the Fluent as a wall. It is important to defined as interior before exported to Fluent software. The fluid inside the CFD model must also be defined to show that there is fluid flow in the CFD model.

Name	Type
Air fuel inlet	Velocity-inlet
Co-flow air	Velocity-inlet
Atomizer wall	Wall
Pressure outlet	Pressure-outlet
Symmetry a	Wall
Symmetry b	Wall
Outer wall	Wall
Default interior	Interior
Fluid	Fluid

Table 2. Name of the boundary condition and types

Volume	Volume 1	Volume 2
Type	Tet/Hybrid	Tet/Hybrid
	Tgrid	Tgrid
	Interval size = 1	Interval size = 0.1

Table 3. Setting for mesh

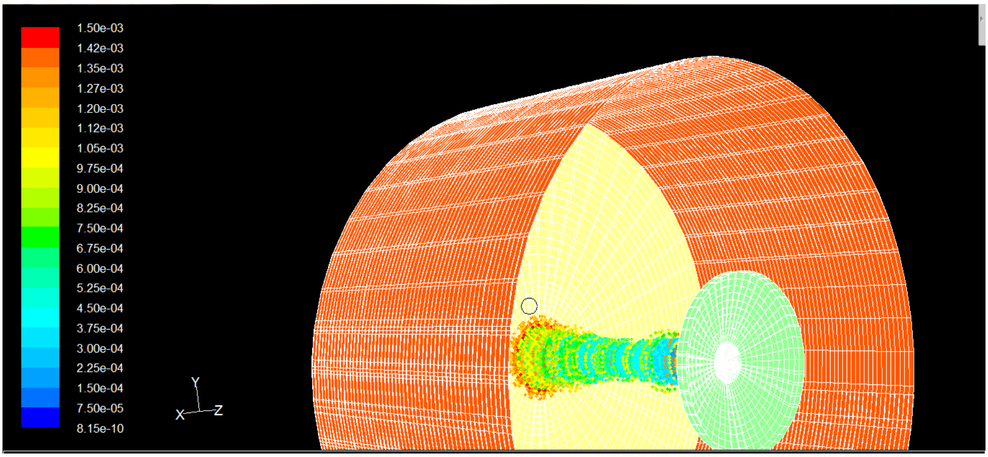

Figure 9. Domain of the spray

3. Results and discussion

3.1. Sauter mean diameter

Sauter Mean Diameter (SMD) is the diameter of a sphere that has the same volume/surface area ratio as a particle of interest or can be defined as the diameter of the droplet whose ratio of volume-to-surface area is equal to that of the spray as stated [30]. The most accurate method to determine SMD of fuels is through the acquisition of a device called Phase Doppler Particle Analyzer (PDPA) system [1]. Due to cost constraints, a SMD formula generated is adopted to study the SMD size, for this research purpose [24]. The chemical properties of the fuels, namely viscosity, surface tension and density will directly affect droplet size of fuels, where viscosity is regarded to have the largest contribution to change the SMD. The correlation for SMD is:

$$\mathrm{SMD} = 6156\, \upsilon_m^{0.385} \gamma_m^{0.737} \rho_m^{0.737} \rho_{\mathrm{A}}^{0.06} \Delta P_L^{-0.54} \tag{1}$$

Where;

ν_m = mixture viscosity (m^2 /s)

γ_{m} = surface tension (N/m)

ρ_m = fuel density (kg/m^3)

ρ_A = air density (1.145 kg/m^3)

ΔP_L = liquid fuel injection pressure difference. (2 bar)

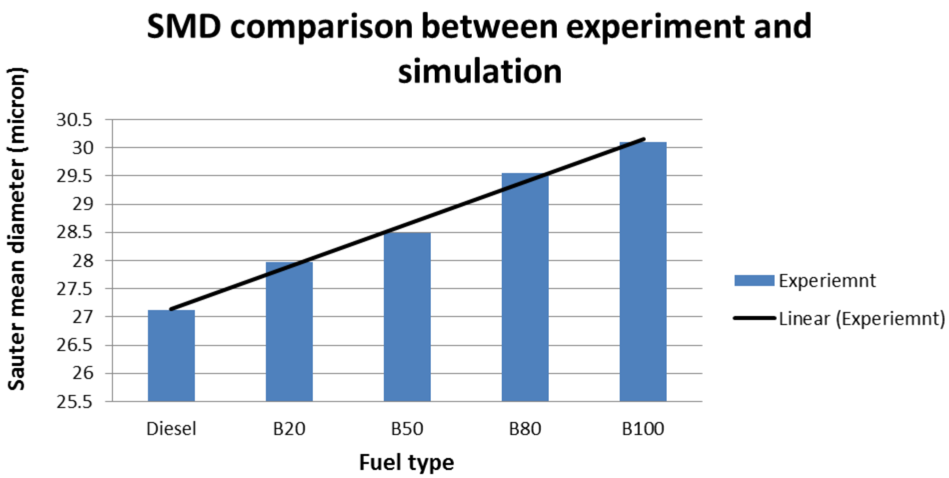

Figure 10. Chart of Sauter Mean Diamater (SMD) for various fuel blends.

Based on the fuel sample prepared, the SMD was calculated for all sample fuel and tabulated results are shown in Figure 10. Pure biodiesel fuel, B100 has the largest SMD, followed by B80, B50, B20 and diesel. The SMD of B100 fuel is derived from WCO in this research and it agree with the SMD of biodiesel fuel derived from palm oil [7]. Sauter Mean Diameter (SMD) of biodiesel blends are much larger when compared to diesel because of the higher value of viscosity and surface tension of biodiesel [26]. The equation used to calculate SMD is used to give a comparable trend between different liquid fuels instead of accurate SMD values which can only be obtained by a complete PDPA system. The higher viscosity and density are responsible for the larger SMD of biodiesels, where the viscosity is regarded to have the largest contribution to the change in SMD it is proved [24]. High viscosity suppresses the instabilities required for the fuel jet to breakup and thus delays atomization. An increase in fuel density adversely affects atomization, whereas high surface tension opposes the formation of droplets from the liquid fuel as discussed [30]. Biodiesel fuel with a high viscosity has fewer droplets due to the breakup frequency, which is relatively low compared to that of diesel fuel [39]. In other words, with the same amount of injected fuel through the atomizer this will produce larger SMD if the amount of droplets is less. Despite of biodiesel having larger SMD, the difference with diesel is small which about 3 microns as obtained from the experiment performed.

Biodiesel has more massive fragments and less fine droplets than those of diesel fuel due to its high liquid viscosity, resulting in high mean droplet size. Consequently, it can be postulated that the breakup characteristic is strongly dominated by not only the surface tension but also the friction flow inside a droplet [37]. To increase the poor atomization of biodiesel fuel compared to diesel due to the larger SMD, ethanol can be blended together with biodiesel to produce smaller SMD. This is because ethanol has lower kinematic viscosity with active interaction with ambient gas. In other words, blending ethanol with biodiesel will enhance atomization characteristics. Referring to the correlation for SMD, fuel mixture viscosity, fuel surface tension and fuel density has obvious impact for the change in SMD. Referring to Table 1, higher ratio of biodiesel in a fuel will correspond to the higher viscosity and density. A fluid's viscosity causes the fluids to resist agitation, tending to prevent its breakup and leading to a larger average droplet size. While density can cause a fluid to resist acceleration, so does other chemical properties such as viscosity, higher density. All this results in a larger SMD of the sample fuel.

In addition, SMD for both biodiesel blended fuels and diesel will be smaller when higher injection pressure is applied during atomization process. A research carried out by Kippax et. al. [20] shows that high injection pressure in the spray system will generate higher actuation velocity of the fuel particles and produce smaller droplet size from the nozzle orifice. Moreover, higher injection pressure leads to an increase in the ambient gas density and the aerodynamics interactions and so the breakup time occur earlier and thus decreases the SMD of the fuel. The general pattern is obtained whereby pure biodiesel (B100) records the highest value of kinematic viscosity and density. These high values recorded for B100 had caused poor atomization with long spray tip penetration, large spray cone angle, large spray width and also large SMD. Results obtained by author could not be directly compared with different researchers due to different atomization pressure applied. The pressure was set at 1,2,3,4 and 5 bar which is 0.1, 0.2, 0.3, 0.4 and 0.5 MPa whereas other researches using a much higher injection pressure ranging from 20 MPa to 300 MPa. Therefore only the general patterns of results were compared instead of the values obtained. This project focused on the comparison of various injection pressure starting from 1 bar until 5 bar and constant injection pressure which is 2 bar. As discussed earlier, SMD will be affected by chemical properties even though the injection pressure is constant and the same result is shown in this project. The larger ratio of biodiesel in the fuel blend gives a larger SMD and vice versa. Thus, this also affects the spray angle, spray width and spray length whereby it resulted in bigger spray angle, spray width and longer spray length. Moreover, this will cause poor atomization for power generation. In the other side, various injection pressures with specific biodiesel blend are specified to compare the SMD result for each injection pressure with specific biodiesel blend. The higher injection the smaller the droplet size even for B100 fuel and this also cause the poor atomization. The best is blending the biodiesel fuel with diesel to get good atomization process.

3.2. Spray cone angle

Spray angle or spray cone angle, is another important atomization parameter in spray analysis. In fluid mechanics, spray angle is defined as angle formed by the cone of liquid leaving a nozzle orifice where two straight lines wrapped with the maximum outer side of the spray [21] and spray cone angle can be defined as the angle between the maximum left and right position at a half length of spray tip penetration from the nozzle tip [35]. Furthermore, according to another researcher stated that biodiesel gives narrower spray angle than diesel fuel [25] and the spray cone angle decreased as the ratio of the biodiesel blend increased [1]. Therefore, the author's experiment result is consistent with other researcher's results. In this research, spray images are captured using a high speed camera, when conducting fuels atomization experiment. Figure 11 shows two spray angles for the experimental and simulation analysis for constant injection pressure. Injection pressure were set to two bar to study the relationship between fuel properties and spray angle. Here, the spray angle for B100 and D100 were compared and it is obvious that the higher content of biodiesel resulted in a smaller spray angle. As the percentage of biodiesel increase, the spray angle with the increase pressure will increase the momentum of the fluid stream upon the activation of the jet spray. Furthermore, constant injection analysis shows that fuel properties will affect the spray angle whereby the higher content of biodiesel gives a smaller spray angle. This result is similar and it is said that B100 or higher content of biodiesel which is relatively viscous, dense and higher surface tension has the smallest spray angle [8]. Meanwhile, the results also concur with another researcher [39] and based on his paper it is reported that when surface tension is low, spray droplet are prone to quicker break up and wider of dispersion, because relatively larger spray angle could be observed. B100 spray angle is much smaller compared with D100 spray angle in this experiment. Fuel properties testing shows that the higher the ratio of biodiesel blend the higher content of viscosity and density. When both of it is higher, it shows that the surface tension increased with biodiesel content in the fuel.

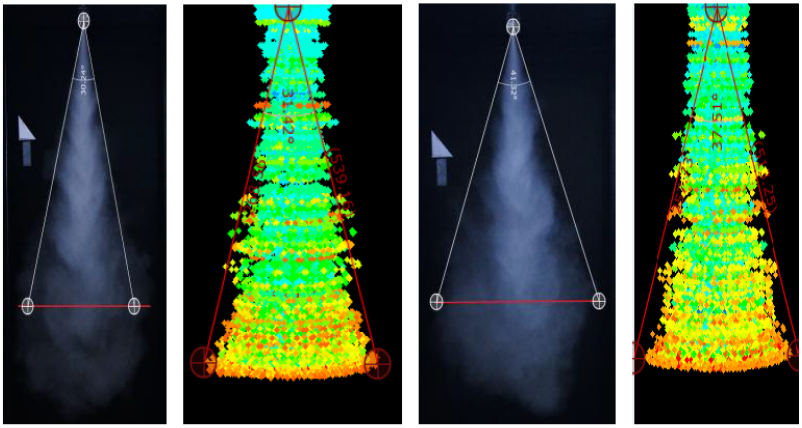

Figure 11. B100 (left) is 30.24° (experiment),31.42 ° (simulation) and D100 (right) is 41.32° (experiment),37.51 ° (simulation) at 0.2 MPa

Therefore, another comparison can be made for various injection pressure to see the relationship between effect of the fuel injection pressure with spray angle. The experimental testing was conducted through various injection pressures and based on the spray cone angle test, the results are tabulated in Figure 12. It can be seen from this figure that the spray cone angle for diesel is the highest among all types of fuel at different injection pressures and decrease of spray cone angle is because of the increased of spray tip penetration and the biodiesel has the spray cone angle less than diesel. Spray angle decrease slightly when ratio or percentage of biodiesel in the fuel increased. B100 has the lowest spray angle compared to other types of fuel at any injection pressure. A fuel spray characteristics research proved that spray angle will decrease irregularly as the biodiesel fraction increase, but inversely with fuel surface tension [22]. When surface tension is low, spray droplet are prone to quicker break up and wider of dispersion, and cause a relatively larger spray angle. The experiment results were supported by researchers [8,21] whose work concentrated on spray biodiesel blended fuel. Axial spray tip penetration of the tested fuels were similar as the spray cone, but B100 which is relatively viscous, dense and higher surface tension has the smallest spray angle compared to diesel and other biodiesel blended fuels. Value of surface tension for all types of fuel provided was assumed constant, at 0.2616 N/m and therefore, the effect of surface tension to spray angle can be negligible in this research.

Meanwhile, the spray angle for all types of fuel increase when higher injection pressure is applied during atomization process. This statement is supported by a researcher [23], whose work emphasize on the injection characteristic using honge methyl ester. Increase in injection pressure will increase the flow rate through the nozzle orifice, which will then decrease the droplet size (SMD) of the fuels and facilitate evaporation. This will result in larger spray angle (larger dispersion area) and a significant increase of spray coverage.

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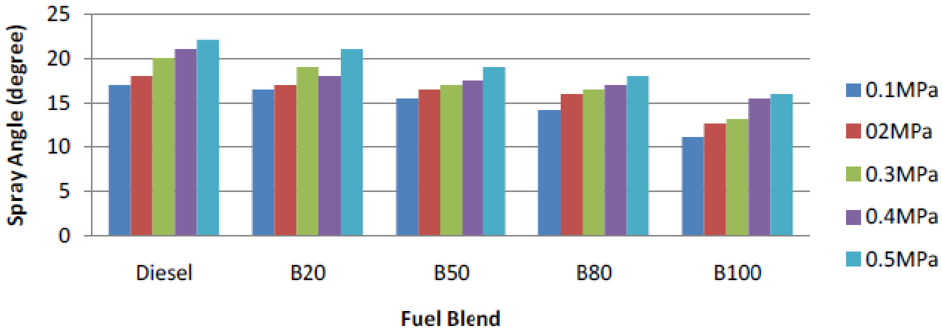

Figure 12. Spray angle for various fuel blends at different injection pressures.

Altercation about the effect of injection pressure on spray angle proved that spray geometries in particular penetration length and cone angle are sensitive to small changes in operating condition and injector geometry. Nozzle inlet condition, nozzle injection angle, nozzle hole dimension will give impact on various atomization characteristics. For instance, the smaller holes size and smaller injection angle of nozzles will produce smaller droplet size and spray angle. The nozzle is a critical part of any sprayer, used to regulate flow, atomize the mixture into droplets and disperse the spray in a desirable pattern. In short, spray angle produced during atomization is not absolutely dependent on fuel properties and injection pressure, but external factors such as the type of nozzle could also affect experimental results.

3.3. Spray tip penetration (Spray width & spray length)

Spray tip penetration is significant atomization characteristic which is used to determine the size or area of atomization. Spray length, spray width and spray pattern are categorized as the three main parameters in spray tip measurement. Spray width is the atomization parameter used to observe area of dispersion of the spray. While spray length, also known as spray distance, measure the travel distance of the liquid fuel when it initiate the first spray from the nozzle orifice. The experiment results for spray width and spray length were collected and tabulated in Figure 14 and Figure 15 through the charts shown. Both these results are qualitative in nature and are based on the drawing from the images captured. Meanwhile, Figure 13 show the length pattern of the spray. The spray penetration of diesel is the lowest for all chamber pressures. This is because the density and viscosity of diesel is lowest amongst all test fuels hence it atomizes more rapidly as compared to other test fuel [40]. Meanwhile, increase in injection pressure will increase flow rate through nozzle orifice, which will then decrease the droplet size (SMD) of the fuel and facilitate evaporation [23].

In Figure 13, the spray width for fuel with higher fraction of biodiesel is smaller than diesel at any injection pressure. There is a close relationship between spray angle and spray width. The larger spray angle will results in larger spray width. In addition, high percentage of biodiesel in a fuel (high viscosity and density) has larger droplet size which can causes poor atomization. This will cause the atomization pattern to have a smaller spray angle and spray width.

However, spray width will be larger when fuel blends are tested at higher injection pressure during atomization process. This result agrees with a researcher [25] which discovered that the increase in injection pressure from 90MPa to 120MPa results in approximately 40% more ambient gas being entrained into the spray system in average. High injection pressure applied through spray system could mitigate undesirable atomization condition since the average particle size of fuel can be broken up into smaller partition and dispersed to larger area of coverage.

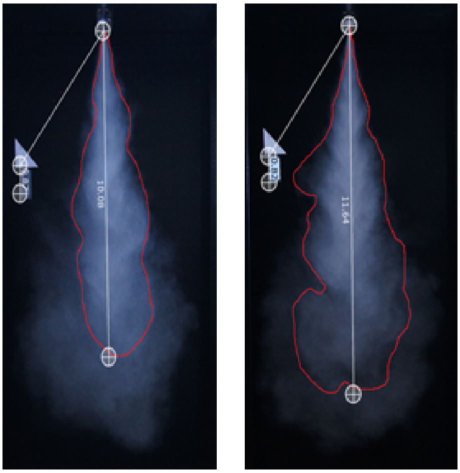

Figure 13. D100 (left) and B100 (right) at 0.2 Mpa

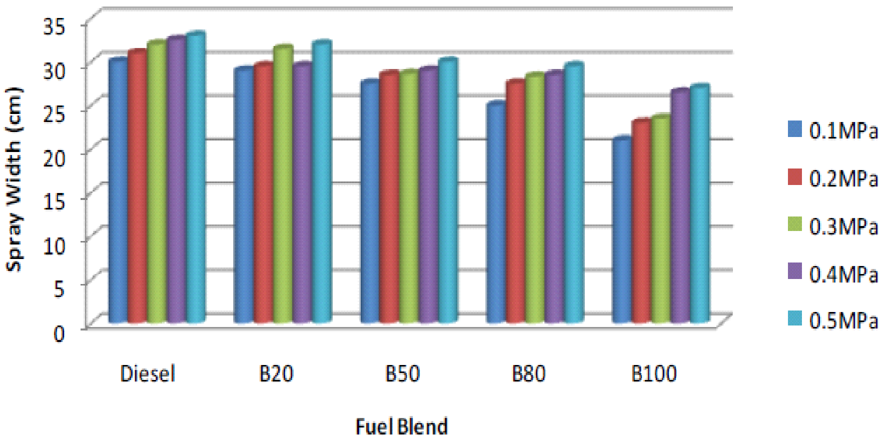

Figure 14. Spray width for various fuel blends at different injection pressures

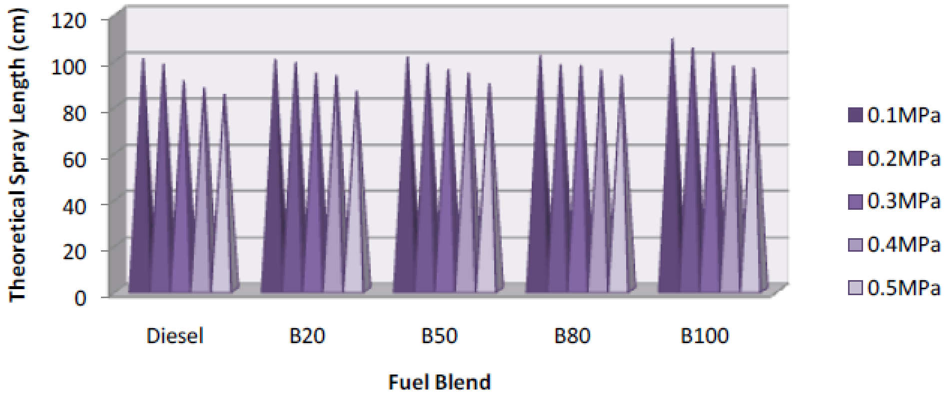

Figure 15. Spray length for fuel blends at different injection pressures based on the experimental results

From Figure 13, spray length for B100 is higher compared to other biodiesel blended fuels and diesel (lowest spray length). Higher fuel viscosity develops a longer potential core and larger face area. This can increase the quality of the atomization by increasing the surface area. Meanwhile, spray length for every type of fuel will decrease when higher injection pressure applied during atomization process. From theoretical spray length formula, spray length is dependent on spray angle and spray width. Spray length is inversely proportional to spray angle and spray width. The larger the spray angle and spray width, the lower the spray length and vice versa due to gravity effect and ambient conditions. Ambient pressure has stronger effect or impact on spray tip penetration than injection pressure. An increase of the ambient pressure will decrease the spray length due to higher air resistance. Since amount or volume of fuel used for atomization process is considered constant, it is reasonable to state that larger area of spray dispersion (spray width) will results in shorter spray length.

3.4. Spray pattern

Spray pattern is the shape of the jet of spray leaving the atomizer or spray gun. The spray pattern can be obtained during atomization experiment by capturing the spray images using high speed camera. Different spray pattern obtained from different blending of biodiesel fuel. Spray pattern analysis is used to characterize types and quality of spray such as spray shape, color intensity of spray, spray speed and others. The photographs of spray pattern in this experiment were captured using an image processing procedure. As shown in Figure 16, spray pattern of diesel fuel is not very visible compared to spray pattern of B100 at injection pressure of 0.5MPa or 5 bars. Fuel with higher blending ratio of biodiesel will develop a longer, denser potential core and quality spray pattern. This is because relatively high viscosity fuel has larger SMD compare to lower biodiesel blended fuel. Presence of intact fuel core indicates that viscous and surface tension forces in biodiesel spray are high enough to suppress disintegration of the fuel core. It was claimed by a researcher [8] that "the vortex shape of biodiesel fuel with high viscosity is clearer than diesel fuel because the breakup frequency of biodiesel fuel is low". Lower break up rate for B100 produce larger droplet size and will cause the spray pattern to become clearer compared to diesel fuel. A clearer spray pattern or large droplet density is associated with overlapped images and fringes in arbitrary direction due to multiple scattering.

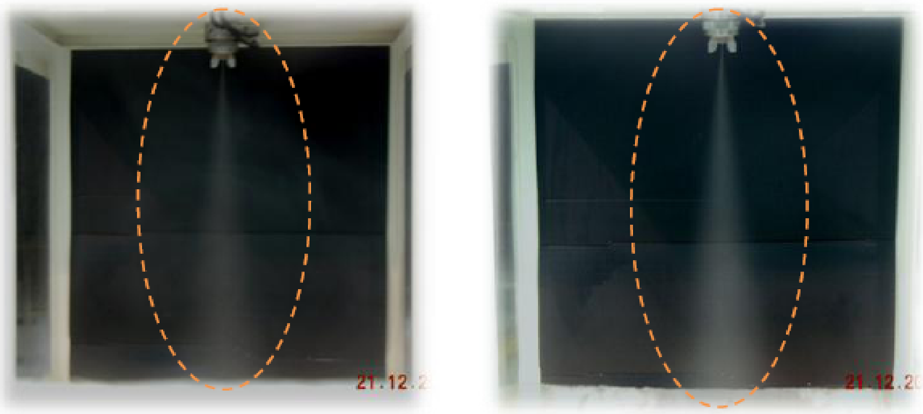

Figure 16. Spray pattern for diesel (left) and B100 (right) at 0.5MPa

On the other hand, higher injection pressure increases the mass flow rate and will then increase the diameter of fuel core. This causes deposition of smaller droplets within the upper canopy near to the nozzle orifice. Therefore, a better quality spray pattern could be observed at higher injection pressure during atomization process. In short, fuel properties are the most important factor that affects spray tip penetration for atomization. Mixture of viscosity and density increase as the biodiesel ratio of fuel increase while the surface tension is relatively insensitive to the biodiesel proportion of the fuel. Dynamic viscosity of a fuel resists change in the shape or arrangement of its elements during flow. Fuel viscosity is the main factor that could affect spray pattern formation, and to a denser degree and capacity. Meanwhile, high viscosity fuel requires a higher minimum pressure to the begin formation of a spray pattern and provide narrower spray angles. Theoretically, higher viscosity of the fuel will cause the injector valve to move slowly due to the larger friction. This will cause the initial spray velocity to decrease, resulting in shorter penetration. However, this concept cannot be completely accepted to evaluate experimental results obtained in this project because external factor such as ambient temperature has substantial impact on atomization characteristics. For instance, high ambient temperature tends to form a more volatile fuel (lower mixture viscosity, specific gravity and surface tension) and finally decrease SMD and spray length of the fuel at constant atomization viscosity and density of the fuel, which can affect the initial spray velocity. This can be explained using fluids dynamic – Bernoulli equation, whereby velocity is inversely proportional to the square root of density. Hence, it can be concluded that atomization characteristics for fuels is not only dependent on experimental atomization factors. The studies on the relationship between ambient pressure and temperature, injection pressure, orifice diameter, nozzle shape and biodiesel content in the fuels are also equally important to be studied.

An open fire test was conducted as preliminary results for the combustion characteristics prediction. The photos captured in Figure 17 shows the test results for open fire test using five types of fuel that had been tested. They are Diesel 100% (D100), 100% biodiesel (B100), 80% biodiesel (B80), 50% biodiesel (B50) and 20% biodiesel (B20). Here, diesel obtained the largest flame structure as compared to B100. But B100 has the most intense and brightest burning capability, most likely due to the higher oxygen content that exist in the fuel. Heat of combustion is the thermal energy that is liberated upon combustion, so it is commonly referred to as energy content. As can be seen, as the biodiesel component in the fuel is increased from 0% to 100%, a concomitant decrease in energy content is observed. Factors that influence the energy content of biodiesel include the oxygen content and carbon to hydrogen ratio. For instance, fatty acid methyl esters (FAME) with 18 carbons in the fatty acid backbone include methyl esters of stearic (largest hydrogen content), oleic, linoleic and linoleic (smallest hydrogen content) acids. Biodiesel fuels with larger ester head groups such as ethyl, propyl or butyl are expected to have greater energy content as a result of their greater carbon to oxygen ratios.

The experiment result shows the same trends with CFD simulation. The spray angle result of experiment shows that the spray angle does not differ much for all five types of fuel. The pattern is maintained whereby D100 has the largest spray angle and BD 100 is the smallest spray angle. A comparison was done between CFD simulation and experiment spray angle result. The spray pattern of the atomization was done using CFD simulation and atomization testing experiment. Both CFD simulation and atomization testing have almost similar spray pattern of the fuel. From the spray pattern, the spray angle can be seen to be smaller from DF100, BD 20, BD 50, BD 80 and BD 100. The spray pattern of five types of fuel using CFD simulation is shown in Figure 18. From the comparison, it can be seen there are some differences in spray pattern between the CFD simulation and experiment result. In addition, spray geometry especially spray angle and spray length is sensitive to small change of operating condition and injector geometry such as nozzle inlet condition, nozzle injection angle and nozzle hole dimension. The nozzle is a critical part of any spray, used to regulate flow, atomize the mixture into droplets and disperse the spray in a desirable pattern. Spray tip penetration of the tested fuels is similar as the spray cone, but B100 which is relatively viscous, dense and higher surface tension has the smallest spray angle [34-37]. Moreover, higher content of viscosity, density and surface tension will give a clearer picture of atomization spray or clear shape spray pattern. Although, the spray is clear but the spray angle is affected whereby it will give a small spray angle. The same situation happened in simulation result. Therefore, purpose of simulation is to compare with the experiment result and other researchers result.

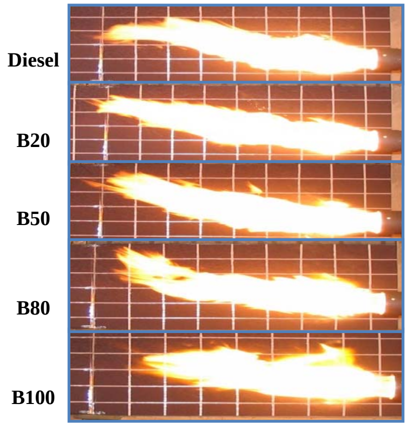

Figure 17. Open fire testing for five type of fuel

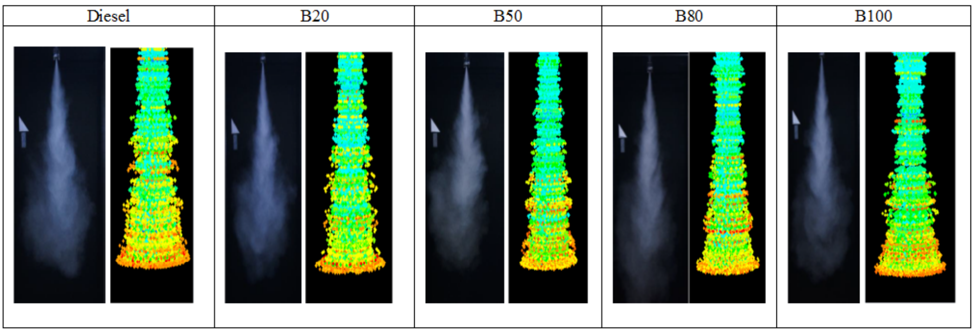

Figure 18. Comparison between experiment and simulation result at 0.2MPa

4. Optimum fuel blend for microturbine engine

With increased interest in emissions and reduction of the use of fossil based fuels, biodiesel fuel blends should be considered especially on ideal atomization for microturbine engine. Impact of effervescent spray characteristics should be taken into consideration. From experimental analysis, the higher the ratio of biodiesel in a fuel, the higher viscosity and density the fuel is. This will result in larger SMD or known as droplet size, smaller spray angle and spray width but longer spray length during atomization process. In order to substitute burning of diesel fuel in a microturbine engine, the viscosity of biodiesel blended fuel oil must be lowered to allow proper atomization and complete combustion process. High viscosity of biodiesel fuel tends to build up carbon on engine and ultimately damage the fuel injection system. A critical factor to be considered in selection of suitable biodiesel fuel blend to be used in microturbine is its oxidation stability. Biodiesel fuels are methyl/ethyl ester oxygenates. The higher the ratio of biodiesel blended fuel, the higher the oxygen content of the fuel. The degree of saturation of fatty acid chains tends to correlate with its stability. Oxidative instability and fuel oxidation during storage not only affect fuel life, but also can lead to deposit formation on injector nozzles, inlet & exhaust valves and other potential engine problems such as premature wear of pistons, segment rings and cylinders, difficult when starting from cold, irregular ignition and others.

Another important factor to be considered in selecting the suitable alternative fuel is fuel consumption, which is directly related to economic factor. A study on the use of biodiesel in combustion engine state that the mixture of diesel oil and pure biodiesel in proportion of up to 10% will result in the reduction of the fuel consumption, and that for greater proportions, there was an increase in consumption of up to as much as 4.77% when pure biodiesel was used [31]. This increase in consumption is explained by the difference in the calorific power of biodiesel, which is generally less than the calorific power of diesel oil. The calorific value of biodiesel which is about 37.27 MJ/L, and thus biodiesel fuels have lower energy content, about 89% of diesel fuel. With respect to environmental consideration, it can be seen that significant reductions in the emission of carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbon (HC), sulphur dioxide (SO_2) and other pollutants can be obtained by biodiesel because carbon, hydrogen, sulphur and nitrogen content of this renewable fuel is relatively lower than diesel fuel. However, smaller spray angle for biodiesel fuels during atomization process and higher injection pressure in internal combustion engine can leads to higher NOx emission. This is because fuels tend to overflow into high temperature region where abundance of oxygen in this section readily oxidizes soot in faster rate.

With extra attention and consideration paid for various important aspects such as technical (atomization characteristics and fuel properties), environment, economic, and global energy issues, the blended biodiesel fuel should be selected due to its availability to reduce emission at certain level of pollutants. The recommended fuel must adhere to ASTM D2880 or similar requirements for gas turbine fuel oil. Experimental investigations showed that B20 is the most ideal alternative fuel to substitute diesel in a micro turbine engine. B20 has the fuel chemical properties very close to diesel especially viscosity which will directly influence spray characteristic such as SMD, spray angle, spray width, spray length and spray pattern. Smaller droplets size of B20 compared to other biodiesel blended fuel provide larger area of fuel air mixing and increase the time available for complete combustion in liquid fuelled combustion system. While smaller spray angle or narrow angle sprays of B20 compare to diesel during atomization could increase spray impingement in the microturbine engine. As a general rule, the narrower the spray angle, the greater the impact of ignition it gives over a given area. Combustion will first be confined for narrow angle spray; while spray penetration length is not the main concern in this selection analysis due to limited burning space of micro turbine engine.

Oxygen content in B20 is at acceptable level compared to other higher blended biodiesel fuel and this will improve oxidation stability and the fuel life. Although calorific value for B20 is lower than diesel, the consumption of B20 fuel in combustion engine is reduced [31]. Hence, B20 fuel is the most suitable biodiesel blended fuel to replace diesel fuel in a micro turbine engine, where the atomization characteristics and engine performance are the main factors to be considered in this research-based selection.

5. Conculsion

Sauter Mean Diameter (SMD), spray angle and spray tip penetration are recognized as the three major atomization characteristics in fuel spray experimental analysis. Theoretical SMD results were obtained via a correlation SMD formula, which were mainly based on chemical properties of the fuels. From experimental analysis, the higher the ratio of biodiesel in the fuel, the higher viscosity, density and surface tension of the fuel. This will result in larger SMD and longer spray length but smaller spray angle and spray width with clearer vortex shape of spray pattern. Fast movement of air surrounding the dispersion of spray will cause movement of spray penetration and unable to reach its maximum tip penetration. The same goes to ambient pressure where higher surrounding pressure will cause the spray leaving the nozzle to disperse in a shorter spray tip penetration. With increment in pressure of air, this will also increase density of air and affects the spray tip penetration as well. Thus the resulting in increment of ambient air pressure [21]. Spray tip penetrations of biodiesel blended fuels showed a similar pattern regardless of the mixing ratio of the biodiesel [34]. The atomization process for biodiesel blended fuel was inferior to that of the conventional diesel fuel due to high surface tension of the biodiesel fuel [36]. In addition, the higher injection pressure applied in atomization tend to break up fuel particles into smaller size, which will subsequently produce larger spray angle and spray width but shorter spray length with denser spray pattern. It shows the same result with other researchers and the result also shows the clearer vortex spray pattern, small spray angle and longer sprays length for higher content of biodiesel.

In general, spray cone angle for diesel is the largest and spray cone angle for biodiesel is smaller. Spray cone angle for biodiesel can further be described as the blending ratio of biodiesel increases, the spray cone angle decreases. This can be due to the higher density of biodiesel compared to diesel. Another physical characteristic that effects spray cone angle is the viscosity of the liquid fuel [10]. At a lower ambient pressure compared to atomization pressure, the spray cone angle produced is also smaller. Furthermore, the general pattern whereby diesel has the largest cone angle and pure biodiesel has the smallest cone angle and SMD for biodiesel fuel are higher compared to conventional diesel oil because of different physical characteristics such as higher viscosity and surface tension for biodiesel [1]. For different blend of biodiesel, as the biodiesel blend ratio increases this will also produce larger SMD due to the differences of viscosity and surface tension. Also SMD of any liquid fuel will also reduce as the atomization or injection pressure increase [38]. All results obtained on atomization characteristics agrees with results obtained by different researchers. Furthermore, fuel properties play an important role in atomization and include kinematic viscosity, density and surface tension. Due to higher kinematic viscosity and surface tension of biodiesel

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compared to diesel, poor atomization is exhibited by biodiesel. This can be solved by increasing injection pressure for biodiesel as breakup rate will increase.

In addition, results obtained shows that spray cone angle for diesel is larger than that of biodiesel due to the increased spray tip penetration of biodiesel. Larger spray tip penetration occurs with a smaller spray cone angle. Meanwhile, larger spray tip penetration of biodiesel is also due to the higher density and viscosity value that reduces breakup rate of the liquid fuel. Droplets produced are larger for biodiesel compared to diesel. B20 was proposed to be selected as the most ideal biodiesel and diesel blended fuel to be applied in microturbine and gas turbine engine due to its adoptability to replace diesel fuel without affecting much of the engine performance. B20 also promote effective atomization characteristics, which are critical to execute proper combustion process. Table 4 show the description of atomization characteristic for better understanding.

Further research works in this field will be concentrated on the implementation of heating the fuel prior to the spray. This will decrease the viscosity of biodiesel and may allow the atomization to be superior for higher blends of biodiesel. Meanwhile, further efforts are being made to enhance the simulation results. Moreover, the PDPA system should be used to obtain the accurate result whereby it can obtain the size of Sauter Mean Diameter and determine the velocity of the spray. Meanwhile, injection pressure also have to be enhanced by increasing the injection pressure into actual injection that will be applied into gas turbine to simulate the actual injection process.

Atomization Characteristics	Increase in Mixture Viscosity and Density	Increase in Surface Tension	Increase in Injection Pressure	Increase in Specific Gravity	Increase in Fluid Temperature
Spray Angle	Decrease	Decrease	Increase	Negligible	Increase
Spray Width	Decrease	Decrease	Increase	Negligible	Increase
Spray Length	Increase	Increase	Decrease	Negligible	Decrease
Spray Pattern	Improves	Negligible	Improves	Negligible	Improves
Spray Velocity	Decrease	Negligible	Increase	Decrease	Increase
SMD	Increase	Increase	Decrease	Negligible	Decrease

Table 4. The atomization characteristic

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