International Journal of Engineering & Technology, 7 (4.35) (2018) 772-776

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET

Research paper



Evaluation of Atomization Characteristics of Second Generation Biodiesel Using Air Blast Atomizer

Gopinathan Muthaiyah [1]*, Kumaran Palanisamy[2]

[1]*Institute of Sustainable Energy (ISE), UNITEN, 43000 Kajang, Selangor, Malaysia*
[2]*Department of Mechanical Engineering, UNITEN, 43000 Kajang, Selangor, Malaysia*
UNITEN R&D, UNITEN, 43000 Kajang, Selangor, Malaysia
**Corresponding author E-mail: gopinathan@uniten.edu.my*

Abstract

Biodiesel is one of the well-known renewable fuels that can be produced from organic oils and animal fats. Biodiesel fuel that meets ASTM D6751 fuel standards can replace diesel for reciprocating engine. On the other hand, biodiesel can also be considered for gas turbine application in power generation. Nevertheless, inferior properties of biodiesel such as high viscosity, density and surface tension results in inferior atomization and high emission which consequently hinders the fuel for gas turbine utilisation and generate higher emission pollutants. Therefore, this work focused on the evaluation of atomization characteristics of second generation biodiesel which is produced using microwave assisted post treatment scheme. The atomisation characteristics of second generation biodiesel was evaluated using air blast atomiser in terms of spray angle and spray length. Subsequently, numerical evaluation was performed to evaluate sauter mean diameter and droplet evaporation time of second generation biodiesel. The results show, atomization characteristics of second generation biodiesel has improved in terms of spray angle and spray length, sauter mean diameter and shorter evaporation time compared to biodiesel which is commonly referred to as first generation biodiesel and fossil diesel.

Keywords: *Atomization; Biodiesel; Renewable Fuel; Sauter Mean Diameter;*

1. Introduction

Increasing energy demand and depleting fossil fuel resources have intensified the effort to find renewable fuels that can substitute fossil fuel for sustainable energy supply in future. Besides that, environmental pollution due to combustion of fossil fuels has caused negative impact to human beings such as global warming due to emission of carbon dioxide (CO_2) and nitrogen oxide (N_2O), acid rain and air pollution. Therefore, replacing fossil fuels with renewable fuel is a strategic way to protect the environment as well as sustain energy supply. Various renewable energy sources have been studied by researchers for instance biomass, biogas, solar, wind energy, geothermal and biofuel. Biodiesel is one of the promising biofuel that can replace diesel fuel for reciprocating engine. Biodiesel is produced from organic oil or animal fats through a chemical process known as "Transesterification" with the presence of a catalyst and methanol. Biodiesel or First Generation Biodiesel (FGB) has been tested extensively in reciprocating engine by many researchers and has reported better performance and emission compared to fossil diesel. Apart from that, biodiesel also can replace distillate diesel for gas turbine application in power generation sector. Biodiesel seems a viable solution for power generation but the information regarding the use of biodiesel in gas turbine is limited [1]. Furthermore, Gupta et al., 2010 have reported biodiesel is an environment friendly fuel that can replace fossil diesel for gas turbine application without any modification required for its fuel system. However, this statement contradicts with Joe et. al., (2010), [2] who performed feasibility studies on biodiesel for aeroderivative gas turbine. Their study expressed concern that, the existence of alkali metals and particulates normally beyond the ASTMD2880 gas turbine fuel specification standard. The presence of alkali metals and particulates can cause turbine hot path corrosion and the particulates left over from the biodiesel combustion can plug off cooling holes within the turbine walls eventually leads to metal erosion. In addition to this, biodiesel is more water loving than diesel. The presence of water in biodiesel can cause detrimental effects on gas turbine such as corrosion and erosion. Furthermore, existing seals and gaskets that are used in gas turbines for diesel firing may not be suitable for biodiesel fuel. Hence, only Viton sealant that is made from non-metal oxides can survive for long periods of biodiesel application. On contrast, FGB has higher viscosity and lower heating value than fossil diesel. Viscosity is a crucial physical property that can attribute to pressure drop in fuel line and also reduction in fuel atomising pressure in combustor during combustion. Biodiesel with greater viscosity tends to produce larger size fuel droplets which will leads to inadequate air fuel mixing, poor atomization and subsequently improper air-fuel ratio which can leads to incomplete combustion [4]. Atomization is the initial stage in combustion process, where atomiser used to produce fine droplets with certain air pressure for complete combustion [5]. The quality of the atomization is influenced by chemical properties of the fuel such as viscosity, density and surface tension [6]. Furthermore, adequate atomization enhances the mixing of air-fuel ratio in a combustion chamber and eventually leads to complete combustion with less air pollutants produced during combustion [7]. Although, biodiesel has been considered a promising alternative fuel for gas turbine utilisation but inherited properties of first generation biodiesel (FGB) such as viscosity, surface tension and density has been a limitation in meeting the gas turbine fuel requirement especially in accordance to ASTM D2880 standards. According to Ejim et. al., (2007), the viscosity, density and surface tension of biodiesel is relatively higher which is up to 120%, 6% and 22%

Copyright © 2018 Authors. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

than fossil diesel and eventually will results incomplete combustion. In a microgasturbine, the fuel preparation involves 3 stages where atomization of liquid fuel is followed by vaporization with hot compressed air and mixing to form combustible mixture [8]. This process occurs in an air blast atomizer with a cylindrical fuel nozzle and an annular air passage surrounding to facilitate vaporization and premixing prior to combustion [9]. Although, microgasturbine is smaller in size compared to conventional gas turbine, but the concept of atomization and combustion in conventional gas turbine is comparable to microgasturbine. A conventional gas turbine combustor consists of an inlet diffuser section, a fuel injector, an air swirler, a primary combustion zone, an intermediate combustion zone, a dilution zone and liner with holes and slots.

Figure 1, depicts the typical fuel injector and spray phenomena that occurs in a microgasturbine. It's obvious that, the atomization process depicted in **Fig.1** is impractical for biodiesel use in gas turbine because sauter mean diameter (SMD) of biodiesel is 5 to 40% greater than distillate diesel which will produces larger droplets in combustion chamber and require longer evaporation time than fossil diesel. This is because, high surface tension of biodiesel resist the formation of small droplets while higher viscosity delays the atomization process [7]. Eventually, it will lead to poor atomization because fuel with longer spray length will require longer evaporation time to be completely vaporized prior to combustion [10]. In conclusion, biodiesel has more inferior atomization characteristics than fossil diesel. Therefore, improvement in physical properties is needed in terms of viscosity, surface tension and density for better atomization besides meeting gas turbine fuel standard ASTM D2880 prior to gas turbine application.

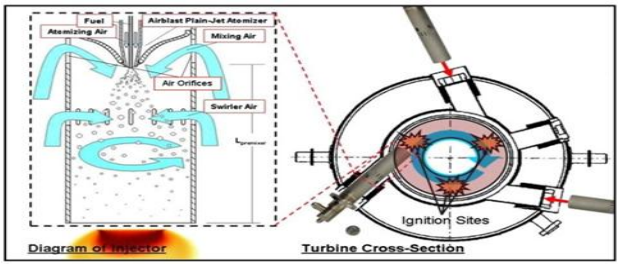


Fig. 1: Air blast spray pattern and Atomiser Configuration in Microgasturbine

Thus, in this study the properties of biodiesel have been improved by altering the fatty acids composition using microwave assisted post treatment scheme (MAPTRES) instead of modifying the existing fuel delivery system. The improvised fuel has been referred as "Second Generation Biodiesel" (SGB) and the properties of SGB fuel has been analysed in accordance to ASTM D2880 gas turbine fuel specification standards. Subsequently, SGB fuel blended with distillate diesel and the atomization characteristics of SGB fuel has been evaluated using air blast atomizer in atomizer rig in terms of spray length, spray angle, SMD and evaporation time. The results obtained for SGB fuel were compared with FGB fuel.

2. Experimental

2.1. Fuel Preparation and Property Evaluation

Used cooking oil (UCO) collected from local food outlets was pretreated to remove unwanted materials and water prior to transesterification process. Subsequently, transesterification was done with methanol and sodium hydroxide as catalyst to produce FGB. The methanol to molar ratio was 6:1 while the catalyst used was 1.0 %wt of the oil. Transesterification was performed approximately for 45 minutes and subsequently the mixture was allowed for separation of biodiesel and glycerine. Then, water washing was performed to the biodiesel to remove excess methanol and remaining unreacted catalyst. Once, FGB fuel is ready approximately 1000 ml of FGB was transferred into MAPTRES for distillation process at selected temperature to produce SGB. The distillation was performed using microwave system to selectively separate certain fatty acids composition for better properties. The distillate sample was collected into a receiving flask for property evaluation at TNB Research Laboratory (TNBR) in accordance to ASTM D2880 gas turbine fuel specification standard while gas chromatography (GC) was performed to determine the fatty acid composition of SGB. Finally, fuels for atomization experiment were prepared based on volume percentage. For example, in order to prepare SGB20, 20% of SGB fuel will be mix with 80% of distillate by volume ratio. Later, the mixture of the fuel was heated with a hot plate at 65 °C to ensure homogenous mixing prior to experiment. **Table 1**, shows the list of fuels prepared for atomization experiment.

Table 1: Type of Fuels for Atomization Experiment

Fuels with Different Blending Ratio	Blending Percentage (%)		
	FGB	**SGB**	**DD**
DD-100	X	X	100
FGB-10	10	X	90
FGB-20	20	X	80
FGB-50	50	X	50
FGB-80	80	X	20
FGB-100	100	X	X
SGB-10	X	10	90
SGB-20	X	20	80
SGB-50	X	50	50
SGB-80	X	80	20
SGB-100	X	100	X

2.2. Atomization Experiment

The atomization experiment was divided into 2 sections, where first, the spray characteristics of SGB was evaluated in an atomiser test rig using air blast atomiser in terms of spray length and spray angle. Subsequently, the SMD and evaporation of SGB fuel droplets were evaluated numerically.

2.2.1 Spray Cone Angle and Spray Length

The atomization experiment was conducted with customised atomisation test rig to evaluate the spray angle and spray length of SGB, FGB and their blends with distillate diesel. The test rig consists major equipment such as compressed air cylinder, air blast atomizer, spray observation chamber, fuel and liquid flow meter, pressure regulator and electronic weighing balance. The purpose of using electronic weighing balance is to measure the mass flow rate of the fuel. In order to conduct the experiment, an air blast atomizer from Capstone C30 had been modified to experimentally investigate the spray angle and spray length of fuel inside observation chamber at 2 different fuel pressure which was 0.5 and 0.8 bar while the inlet air temperature was maintained at 23.8°C to 24.2°C. High speed camera was used to capture the spray length and spray angle during the experiment as shown in **Figure 3** and **Figure 4**. Each experiment was repeated for five times to obtain accurate results. The position of the camera and camera angle was maintained throughout the experiment to prevent any deviation in the image. **Figure 2**, shows the schematic diagram of atomizer rig which is consists of compressed air line and fuel line. During the experiment, the fuel and pressure regulated as per microgasturbine actual operation at full load.

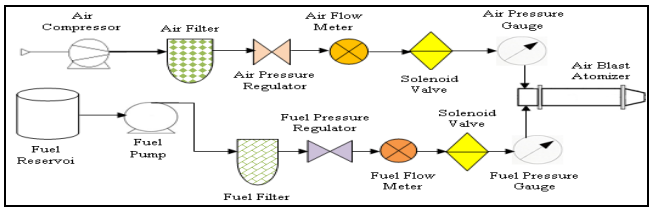


Fig 2: Schematic Diagram of Atomiser Rig

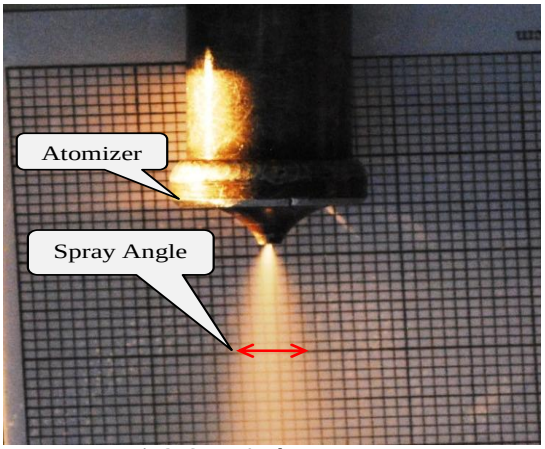


Fig 3: Spray Angle Measurement

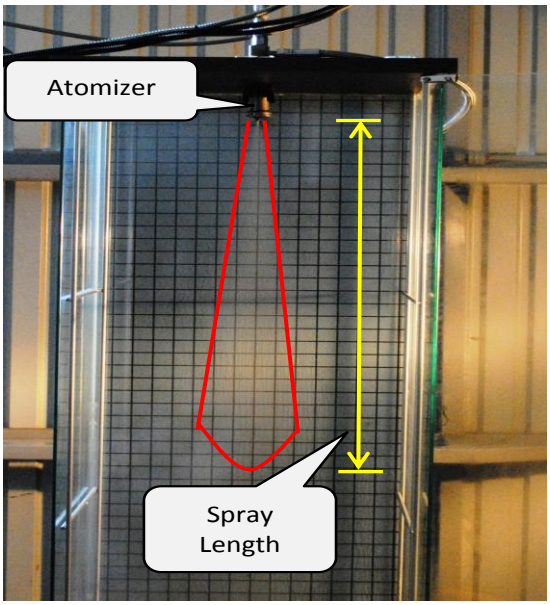


Fig 4: Spray Length Measurement

2.2.2 Sauter Mean Diameter (SMD) and Droplets Evaporation

Sauter mean diameter (SMD) is widely used to evaluate the atomisation characteristics of fuel. It is represents the droplet size of the fuel which can be determine using Phase Doppler Anemometer (PDA) or Laser Doppler Anemometer (LDA) [11]. However, for this study, numerical evaluation was done using Lefebvre correlation as shown in (Eq.1) in order to determine the SMD of the fuel. Similar correlation was adapted by Bolszo [12] to determine the SMD of diesel fuel in microgasturbine and the experimental results were validated through Phase Doppler Anemometer (PDA). In order to use the Lefebvre correlation, air to liquid ratio (ALR) and relative co-flowing velocity data was taken from previous data reported by Bolszo [13].

$$\frac{D_{32}}{d_o} = 0.48\left(\frac{\sigma}{\rho_A U_R d_0}\right)^{0.4}\left(1+\frac{1}{ALR}\right)^{0.4} + 0.15\left(\frac{\mu^2 L}{\sigma\rho_L d_0}\right)^{0.5}\left(1+\frac{1}{ALR}\right) \quad (1)$$

D_{32} = Sauter Mean Diameter, d_o = Liquid Fuel Discharge Opening Diameter (m), ρ_A = Air Density (kg/m^3), U_R = Relative coflowing velocity at injector (m/s), ALR = Air to liquid ratio, σ = Liquid surface tension (N/m), ρ_L= Liquid density (kg/m^3), μ_L= Dynamic Liquid viscosity (m^2/s)

In order to perform SMD evaluation using Lefebvre correlation properties of SGB fuel like surface tension, viscosity and density have been obtained from previous reported work by Gopinathan [14]. The details of fuel properties is given in the subsequent section. Meanwhile, liquid discharge opening diameter for air blast atomiser was measured at SIRIM laboratory using electronic microscope. Apart from SMD evaluation, evaporation time of SGB fuel calculated based on Bolszo works where the similar method was used by Bolszo to determine the time taken to evaporate the diesel fuel in microgasturbine prior to combustion. The details of (Eq.2) is given below and effective evaporation constant (λ_{eff}) was obtained based on previous work reported by Bolszo [12][15].

$$t_e = \frac{{D_0}^2}{\lambda_{eff}} \quad (2)$$

λ_{eff} = Effective evaporation constant, D_0^2 = Sauter Mean Diameter, t_e = Effective evaporation time

3. Results and Discussion

3.1. Property Evaluation of SGB Fuel

Table 2: Property Evaluation of SGB

PROPERTY	METHODS	ASTM D2880 LIMITS	DD	FGB 100	SGB 100
Density @ 15°C	ASTM D4052	0.8760 max	0.8454	0.8758	0.8740
K. Viscosity 40° C	ASTM D445	1.9-5.5	3.906	4.60	4.40
Water and Sediment	ASTM D2709	0.05 max	0.007	0.068	0.374
Surface Tension	ASTM 3606	NA	23	30	28
Saturated Compounds	%	NA	-	42.64	58.77
Unsaturated Compounds	%	NA	-	57.36	41.23

Table 2, shows the property results of SGB, FGB and distillate diesel. Based on the results, SGB fuel has shown improved physical properties in terms of viscosity, surface tension and density. Apparently, distillation using microwave system has enhanced the properties of SGB by altering the fatty acids methyl ester composition of biodiesel by changing more unsaturated compounds to saturated compounds. It is because the physical properties of biodiesel fuel is dependent on the origin of fatty acids composition of the fuel; thus by altering the fatty acids composition through microwave distillation process has changed the physical properties of the fuel [14]. Overall, SGB fuel has better physical properties than FGB in terms of density, viscosity and surface tension and meets ASTM D2880 gas turbine fuel specification standard. All these properties are very important for atomization characteristics.

3.2 Spray Cone Angle and Spray Length

The spray characteristics of SGB, FGB and their blends with DD were evaluated experimentally by determining the spray angle and spray length [17]. **Figure 5**, shows the results of spray angle and spray length for FGB, SGB and their blends with DD. Based on the results, FGB100 has recorded the lowest spray angle compared to other fuels. Moreover, the spray angle of FGB tends to decrease consistently when the percentage of FGB increases in DD. The results evidently correspond with Tan et. al., (2011) [18], where spray angle decreases slightly when percentage of biodiesel increases in the fuel. This result proofs that biodiesel with higher viscosity, density and surface tension leads to poor atomization in terms of spray angle and spray penetration length [20]. On another note, Som et. al., (2010) had claimed that higher velocity of biodiesel (FGB) resulted in loss of flow efficiency and reduction in

injection velocity which will eventually produce longer spray penetration length and lower cone angle. On other hand, the spray angle for all fuels increased when the atomizing air pressure increased from 0.5 bar to 0.8 bar due to higher atomizing air pressure which enhance the rate of fuel break up at atomizer tip and produce smaller droplet (SMD) of the fuels and subsequently enable shorter evaporation time [20].

Meanwhile, the spray angle of SGB increases as the blend ratio increased in DD except for SGB80. Based on the results, SGB20 has comparable spray angle with DD and the highest spray angle was obtained for SGB50. It is worthwhile to note that, improvement in physical properties improved the spray angle of SGB. This is because when the surface tension is low, the spray droplets are break up quickly and wider dispersion angle will be formed for a larger spray angle [18]. Moreover, viscosity has the most dominating effect compared to the density and to achieve improved atomization the viscosity should be the first choice of fuel property to be improved [16]. This statement is in line with current findings where by improving the viscosity, the spray characteristics of SGB has been improved significantly compared to FGB and its blend.

Theoretically, wider spray angle or dispersion angle will cause shorter spray length and vice versa. Apparently, the results obtained for SGB fuel meets the statement where SGB with wider spray angle has shorter spray length. On the contrary, FGB with smaller spray angle has longer spray length. Overall, FGB has longest spray length compared to SGB and DD. It is because FGB with greater surface tension, viscosity and density tend to have higher SMD due to lower fuel break rate to form smaller droplets than SGB and distillate diesel [22]. Furthermore, high surface tension of biodiesel resist the formation of fine droplets from the liquid [7]. This effect eventually produce fuel droplets with higher SMD which contain higher momentum and thus enable longer penetration length with extended evaporation time [24].

Figure 5 depicts the measured and predicted spray penetration length of biodiesel in comparison with diesel. However, improvement in physical properties in terms of viscosity, density and surface tension has improved the spray characteristics of SGB in terms of spray angle and spray length compared to FGB and its blend.

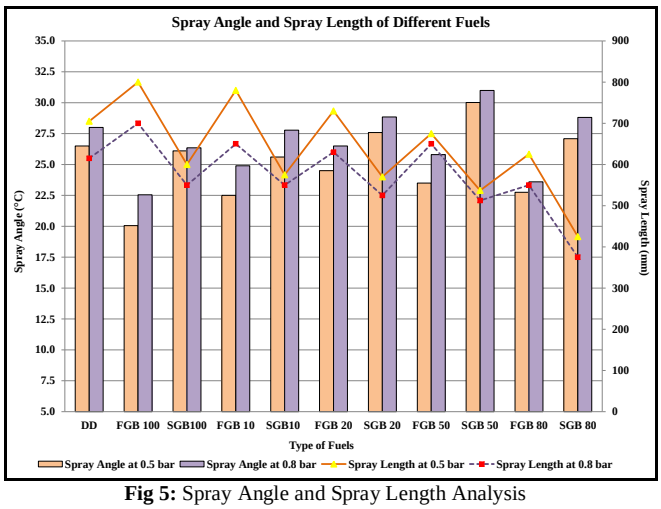


Fig 5: Spray Angle and Spray Length Analysis

3.2. Sauter Mean Diameter Analysis

Numerical evaluation was determined using fuel properties tabulated in **Table 2** and based on the property results, diesel has the lowest surface tension, density and viscosity compared to FGB and SGB. However, it is worthwhile to note that, SGB possesses better properties than FGB in terms on viscosity, surface tension and density while the most significant reduction was found for viscosity of SGB which is 30% lower than FGB. This could attribute to lower SMD for SGB because viscosity is one of the crucial factors that attribute to higher SMD [18]. Fig 6 shows that, SMD of test fuels is in accordance to different blend ratio at air fuel ratio (ALR) 0.22. The results meet in good agreement with previous work where DD has lowest SMD and the SMD increases consistently when the percentage of FGB increased in DD [18]. Larger SMD was obtained for SGB and FGB due to higher viscosity and surface tension compared to diesel [24].

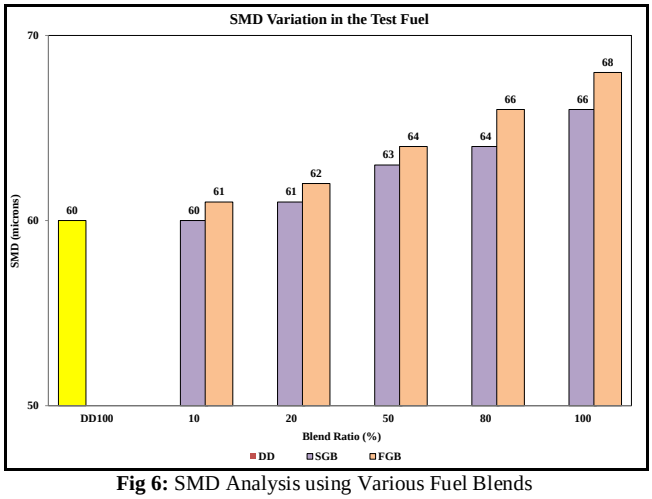


Fig 6: SMD Analysis using Various Fuel Blends

Nevertheless, SGB and its blend exhibit lower SMD values than FGB and its blend. This affirms that, improvement in physical properties has reduced the SMD of SGB slightly compared to FGB. However, it should be noted that not only viscosity, but surface tension is also equally important to reduce SMD of the fuel [13]. Thus, reduction in surface tension of SGB would produce smaller droplets (SMD) compared to FGB. Interestingly, the SMD of all fuels tend to decrease steadily as the ALR varies from 0.2 to 0.65 as shown in **Fig 7**. This is because at higher load the atomizing pressure increases and enhances the fuel break up frequency at atomizer tip and produces smaller droplets [12][13].

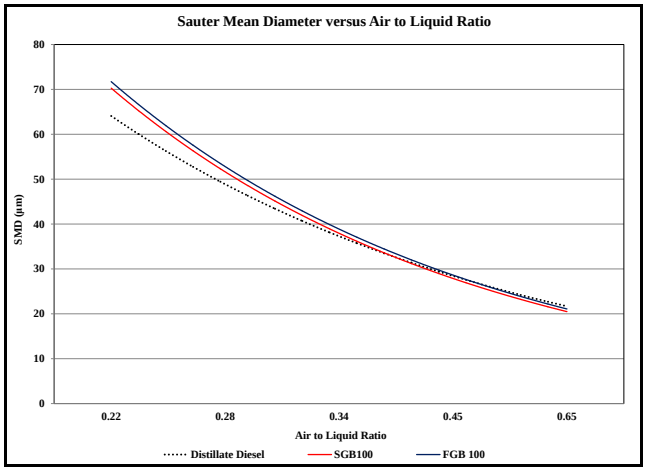


Fig 7: SMD versus ALR

3.3 Droplet Evaporation Analysis

Droplet evaporation was directly influenced by the SMD of the fuel where higher SMD tend to have longer evaporation time. Similarly, Lefebvre stated the combustion efficiency will increase with smaller droplets because smaller droplets will increase the evaporation rate of the fuel [1]. However, previous experimental shows that ideal premixing and pre-vaporization in microgasturbine during full load operation required 11ms for the droplets to be completely vaporized with SMD 50µm [12]. Data reported by

Bolszo, used as reference value to determine the evaporation time of FGB and SGB in microgasturbine.

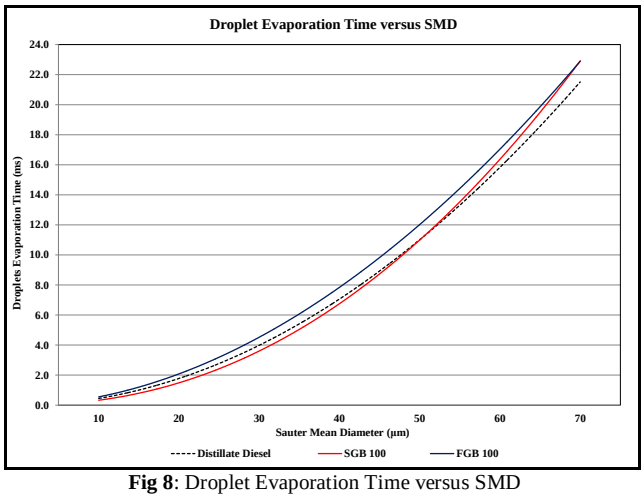


Fig 8: Droplet Evaporation Time versus SMD

Figure 8, illustrates the droplet evaporation time of DD, FGB and DD in microgasturbine. It is observed that, during full load, diesel fuel and SGB required 10ms for 50µm droplets to be fully vaporized whereas FGB required 12ms. This is an evidence to show that higher SMD of FGB attributed to longer evaporation time compared to SGB. Apart from that, FGB has higher melting point than SGB, where fuel with higher melting point do not attain temperature equilibrium in the first 50ms, thus the diameter of droplets remain constant and the evaporation starts later [24]. In conclusion, SGB fuel possesses better SMD than FGB and consequently has shorter evaporation time than FGB.

4. Conclusion

SGB fuel produced through MAPTRES has better physical properties than FGB fuel in terms of viscosity, density, surface tension and meets ASTM D2880 gas turbine fuel specification standards. Subsequently, the atomization characteristics of SGB fuel was evaluated in atomiser rig using actual air blast atomiser. The results shows, SGB fuel has wider spray angle and shorter spray penetration length compared to FGB. Among all other blends, SGB 20 has comparable spray angle and spray length with DD. Moreover, numerical analysis using Lefebvre correlation proves that, SGB has smaller SMD than FGB which consequently improved the pre-vaporization of droplets where droplets of SGB possessed shorter evaporation time compared to FGB.

Acknowledgement

Authors would like to thank University Tenaga Nasional for funding this research through Internal Grant (J510050776) and UNITEN-IRMC who always supported the researchers and monitored the progress of this project from time to time. Besides, the authors would also like to thank UNITEN final year students for their contribution in assisting data collection for this study.

References

[1] Gupta, K.K., Rehman, A., Saviya, R.M., 2010. "Bio-Fuels for the Gas Turbine: A Review", Renewable and Sustainable Energy Reviews, vol.14, pp.2946-2955.

[2] Joe, F.S., Rachel, T.F., and James, K.D. 2010. Liquid biofuels in the aeroderivative gas turbine. Texas USA.

[3] Prussi, M., Chiaramonti, D., Riccio, G., Martelli, F., Pari, L., 2012. "Staright Vegetable Oil Use in Micro-Gas Turbine:System Adaption and Testing", Applied Energy, vol.89, pp.287-295.

[4] Glaude, P.A., Fournet, R., Bounaceur, R., Moliere, M., 2010. "Adiabatic Flame Temperature from Biofuels and Fossil Fuels and Derived Effect on NOX emissions", Fuel Processing Technology, vol.91, pp.229-235.

[5] Allen, C. A. W. & Watts K. C., 1999. "Comparative analysis of the atomization characteristics of fifteen biodiesel fuel types", Proceeding of ASAE 0001-2351, vol.43(2), pp.207-211.

[6] Lin, Y.S. & Lin, H.P., 2010. "Study on the Spray Characteristics of Methyl Ester from Waste Cooking Oil at Elevated Temperature", Renewable Energy, vol.35, pp.1900-1907.

[7] Ejim, C. E., Fleck, B. A., Amirfazli, A., 2007. "Analytical study for atomization of biodiesel and their blends in a typical injector Surface Tension and viscosity effects", Fuel, vol. 86, pp. 1534-44

[8] Bolszo, D.C., McDonell, V., and Samuelsen, S., (2007b), 'Impact of biodiesel on fuel preparation and emissions for a liquid fired gas turbine', Proceeding of ASME Turbo Expo 2007.

[9] Krishna, C.R., (2007b) "Report of Atomization Tests for Biodiesel Blends in Microturbine". Brookhaven National Laboratory, January 9, 2007, Retrieved 25 July 2010 from www.osti.gov/bridge/servlets/purl/909959-bW6MJJ.

[10] Bolszo, D.C., McDonell, V., and Samuelsen, S., (2007b), 'Impact of biodiesel on fuel preparation and emissions for a liquid fired gas turbine', Proceeding of ASME Turbo Expo 2007.

[11] Allen C A W, Watts K C, Comparative analysis of the atomization characteristics of fifteen biodiesel fuel types ASAE 0001-2351 Vol **43**(2) 207-211

[12] Bolszo C D 2009 Investigation of atomization mixing and pollutant emissions for a microturbine engine Research UCI undergraduate research journal.

[13] Krishna C R, 2007. A report on atomization tests for project titled Biodiesel blends in microturbine Brookhaven National Laboratory.

[14] Gopinathan M., Kumaran P., Ibrahim H., Hamdan., Preliminary Property Evaluation of Second Generation Biodiesel for Gas Turbine, SCOReD UNITEN October 2010, Malaysia.

[15] Bolszo C. D, McDonell V. G., 2009. Emissions optimization of a biodiesel fired gas turbine. 2949-2956

[16] Yung S.L., Hai-Ping L., 2010. "Study on Spray Chracyeristics of Methyl Ester from Waste Cooking Oil at Elevated Temperature". Renewable Energy,vol.35, pp1900-1907.

[17] Nowak D., Dobski T., Slefarski R., Magni F., 2010, Spray Generator For The Liquid Fuel Combustion, Proc. of 7th Int. Conf. on Multi. Flow, ICMF, Tampa, FL, USA, May 30-June 4

[18] Tan, E.S., Zulhairi, M.A., 2012. "Feasibility of Biodiesel as Microturbine Alternative Fuel Through Atomization Characteristics Study", Proceeding of ASME Turbo Expo 2012, June 11-15, Copenhagen, Denmark.

[19] Pandey, R.K., A.Rehman., Sarviya, R.M., 2012. " Impact of Alternative Fuel Properties on Fuel Spray Behavior and Atomization', Renewable and Sustainable Energy Reviews, vol,16, pp1762-1778.

[20] Panchasara, H.V., Simmons, B.M., Agrawal, A.K., 2008. "Combustion Performance of Biodiesel and Diesel Vegetable Oil Blends in a Simulated Gas Turbine Burner", Proceedings of ASME Turbo Expo 2008, Berlin, Germany.

[21] Kumaran, P., Gopinathan, M., N.M. Razali., Isabel, K., Hariffin, B., and Hamdan, H. 2013. "Preliminary evaluation of atomization characteristics of improved biodiesel for gas turbine application". Proceeding of International Conference on Energy and Environment, University Tenaga Nasional. 5-6th March 2013, ICEE: 2013-024.

[22] Cheng, Z., Zehao, F., Wen'an, M., Mingzhi, Z., Chenglong, T., Zuohua, H., 2018. "Experimental Investigation on Effect of Ethanol and Di-Ethyl Ether Addition on Spray Characteristics of Diesel/Biodiesel Blends under High Injection Pressure", Fuel, vol.218, pp1-11.

[23] Som, S., Longman, D.E., Ramirez, A.I., Aggarwal, S.K., 2010. "A Comparison of Injector Flow and Spray Characteristics of Biodiesel Blended with Petrodiesel", Fuel, vol. 89, pp. 4014-4024.

[24] Barata, J., 2008. "Modeling of Biofuel Droplets Dispersion and Evaporation", Renewable Energy, vol.33, pp.769-779.