Preliminary Evaluation of Atomization Characteristics of Improved Biodiesel for Gas Turbine Application

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Abstract. Biodiesel is one of the clean burning alternative fuels derived from natural resources and animal fats which is promising fuel for gas turbine application. However, inferior properties of biodiesel such as high viscosity, density and surface tension results in inferior atomization and high emission, hence impedes the fuel compatible for gas turbine application and emits slightly higher emission pollutants due to inferior atomization. This research work focuses on preliminary evaluation of the atomization characteristics of derived from Malaysian waste cooking oil which is the physical properties are subsequently improved by a microwave assisted post treatment scheme. The results shows with improvement in physical properties achieved through the post treatment, biodiesel exhibits significantly better atomization characteristics in terms of spray angle, spray length, sauter mean diameter and shorter evaporation time compared to the biodiesel before improvement and fossil diesel.

1. Introduction

Biodiesel is an alternative fuel produced from renewable resources have recently drawn significant consideration for power generation gas turbine application \cite{1}[2]. However, biodiesel or herein after referred as First Generation Biodiesel, (FGB) in this work, has inferior properties such as viscosity, surface tension and density of biodiesel impede the fuel for gas turbine application \cite{3}. Allen \cite{7} claims that, sauter mean diameter (SMD) of biodiesel vary from 5 to 40\% higher than diesel which is due to higher viscosity, surface tension and density which results in poor atomization and eventually leads to incomplete combustion. The atomization and evaporation of the fuel spray plays an important role in enabling adequate the mixing of air fuel in combustion chamber which directly affect the engine performance and emissions characteristics \cite{4} \cite{5}. In previously reported work by Gopinathan \cite{6}, the improvised biodiesel or called “Second Generation Biodiesel”, (SGB) produced by a microwave assisted post treatment scheme (MAPTRES) has significantly improved properties such as viscosity, density and surface tension, favorable to gas turbine application and meets ASTM2880 fuel specification standard. Correspondingly in this work, the atomization characteristic of SGB has been evaluated in terms of spray angle, spray penetration length, SMD and evaporation time of fuel droplets based on microgas turbine Capstone C30 operation data and compared with FGB and distillate diesel(DD) used as gas turbine fuel.

2. Methodology

2.1 Numerical Evaluation of Atomisation Characteristics & Droplet Evaporation Time
An atomization characteristic is determined via sauter mean diameter (SMD) which is defined as diameter of sphere that has the same volume/surface area ratio as a particle of interest [7]. Numerical evaluation has been done using SMD formula generated by Lefebvre correlation as shown in equation 1. The correlation is adopted to evaluate the SMD because the similar correlation used in works reported by Bolszo [8] to evaluate SMD of diesel fuel in microgasturbine Capstone C30 with air blast atomizer which was experimentally validated using Phase Doppler Anemometer (PDA) [8]. The details of Lefebvre correlation described accordingly and in order to evaluate SMD of SGB, air to liquid ratio (ALR) and relative co-flowing velocity exiting ($U_R$) value adopted from Bolszo works [10].

$$\frac{D_{32}}{d_o} = 0.48 \left( \frac{\sigma}{\rho_A \cdot g \cdot d_2} \right)^{0.4} \left( 1 + \frac{1}{\text{ALR}} \right)^{0.4} + 0.15 \left( \frac{\mu_L}{\rho_L \cdot d_2} \right)^{0.5} \left( 1 + \frac{1}{\text{ALR}} \right)$$

(D$_{32}$ = Sauter Mean Diameter, $d_o$ = Liquid Discharge Opening Diameter (m), $\rho_A$ = Air Density (kg/m$^3$), $U_R$ = Relative co-flowing velocity (m/s), ALR = Air to liquid ratio, $\sigma$ = Liquid surface tension (N/m), $\rho_L$ = Liquid density (kg/m$^3$), $\mu_L$ = Dynamic Liquid viscosity (m$^2$/s))

The fuel properties for the numerical evaluation have been adopted from previously reported work by Gopinathan [6] and the dimensions for the actual injector of microturbine Capstone C30 has been measured at SIRIM laboratory. In this reported work, SGB possess lowest surface tension than FGB and DD which is 15 mN/m, 31 mN/m and 28 mN/m respectively. Besides that, SGB also has kinematic viscosity of 4.5 mm$^2$/s lower than FGB which is 6.6 mm$^2$/s. Additionally, slight improvement was observed for density of SGB 0.8756 kg/m$^3$ compared to FGB is 0.8776 kg/m$^3$, even density has least affects than viscosity [6]. Overall, SGB has better physical properties than FGB and meets ASTM2880 and ASTM6751 standard Bolszo’s method was adopted again to evaluate the evaporation time of SGB and compared with diesel fuel. The details of equation 2 given below and effective evaporation constant ($\lambda_{eff}$) calculated based on reported data by Bolszo [3],[8].

$$t_e = \frac{D_o^2}{\lambda_{eff}}$$

($\lambda_{eff}$ = Effective evaporation constant, $D_o^2$ = Sauter Mean Diameter, $t_e$ = Effective evaporation time)

2.2. Experimental Investigation of Spray Angle & Penetration Length

The atomization test rig was designed and developed to investigate the spray angle and penetration length of SGB100, FGB100 and distillate diesel. The equipment comprises of air cylinder, air blast atomizer, observation chamber, fuel and liquid flow meter, pressure regulator and electronic weighing balance. The electronic weighing balance (Brand : AND ; Model : GF-6000; with super hybrid sensor) used for fuel mass flow rate measurement and volume measured by flow meter (Brand : Mcmillan; Model: S-111-5 with accuracy ± 0.5% and flow range 5-500ml). Air blast atomizer which is the fuel injector from Capstone C30 has been used to experimentally evaluate the spray angle and spray penetration length of fuel inside observation chamber according to actual engine operation condition at selected load 10, 15, 20 and 25kW at inlet air temperature of 23.8°C to 24.2°C. During atomization test spray images captured using high speed camera to measure the spray length and spray angle.

3. Results and discussion

3.1. Sauter Mean Diameter (SMD) and Droplets Evaporation

The results were presented in Figure 1 and 2 respectively. The patterns of all fuels are identical where SMD decreased gradually as the ALR varies from 0.2 to 0.65. Expectedly, SGB has smaller droplets than FGB that has high viscosity and surface tension which causes the fluid resists agitation, tending to prevent its break up and leading to larger droplets [6]. Results shows SGB have better atomization because lower surface tension, viscosity and density will enhance spray break up and eventually would produce smaller Sauter mean diameter SMD [7]. Droplets evaporation time is another crucial element
that that influences the combustion and it’s dependent on droplet size of the fuel and SMD directly influence the droplets evaporation time.

**Figure 1.** Sauter Mean Diameter versus Air to Liquid Ratio.

Fuel with higher SMD tends to have longer evaporation time and eventually leads to incomplete combustion which will results in high emission pollutants. According to Bolszo, the ideal residence time to the fuel droplets to be fully vaporize in microgasturbine with diesel fuel is 2ms (milliseconds) with SMD less than 25μm and the reported work indicates that ideal pre-vaporization cannot be achieve in microgasturbine because at full load Capstone C30 required 11ms for the droplets with SMD 50μm to be fully vaporize [8]. Interestingly, Bolszo’s method adapted for this numerical analysis has shown that the SGB fuel with lower SMD the evaporation time is reduced significantly compared to diesel. Based on the results, at full load diesel fuel required 11ms for 50μm droplets to be fully vaporized whereas SGB only required 7ms. Therefore, SGB has better atomization characteristics than diesel and FGB although the result doesn’t meet the ideal evaporation time of 2ms.

### 3.2. Spray Cone Angle and Spray Length

Spray angle 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 while spray length defined as the greatest distance of the fuel propagates once injected into stagnant air. Nowak [9] reported the key factors determining the efficiency of atomization are droplets size (SMD), spray length, and spray cone angle and evaporation time. The results of spray angle and spray length are presented in Figure 3 and 4.

**Figure 3.** Spray Angle at Various Loads.

Interestingly, SGB and distillate diesel has similar spray angle at 25 kW which is apparently due to improvement in physical properties of SGB. Correspondingly, the low surface tension is prone to quicker break up into droplets and wider of dispersion which will cause a relatively larger spray angle,
at nozzle exit. FGB has lowest spray angle compared to SGB and distillate. Meanwhile, spray angle for all fuels increase when the load increased because during actual operation in microgas turbine the atomizing air pressure increases when the load is increased. The air pressure increase which will enhance the fuel break up frequency at atomizer tip and produce smaller droplet size (SMD) of the fuels and facilitate evaporation and result in larger spray angle and significant increase of spray coverage. On the other hand, SGB with larger spray angle has shorter spray length while FGB with smaller spray angle has longer spray length since it is inversely proportional to spray angle where larger area of spray dispersion will result in shorter spray length[10]. Based on the results, FGB has longest spray length compared to SGB and distillate diesel. This phenomenon also affirms that FGB with high surface tension and viscosity tend to have lower break frequency than SGB and distillate diesel. Consequently, this will lead to inferior atomization because fuel and also cause longer evaporation for completely vaporize the fuel droplet prior to combustion.

4. Conclusion
Atomization characteristics of improved biodiesel SGB have been evaluated and established that improvement in physical properties such as viscosity, surface tension and density has consequently improvised the atomization characteristics of SGB compared to diesel and FGB. Numerical analysis to determine SMD using Lefebvre equation prove and pre-vaporization of droplets resulting in shorter evaporation time compared to diesel that SGB has smaller SMD than diesel. Experimental analysis on spray angle and spray length has shown SGB has wider dispersion angle and shorter spray length due to lower surface tension and viscosity. Therefore, SGB has superior atomization characteristics than diesel and FGB and it has potential to replace distillate diesel for gas turbine application for power generation. Further work recommended to measure SMD with Laser Doppler Anemometer (LDA) for comparison with numerical analysis is to verify the validity of Lebfebrev correlation in SMD analysis.

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