An Assessment on Temperature Profile of Jet-A/Biodiesel Mixture in a Simple Combustion Chamber with Plain Orifice Atomiser

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Abstract. The preliminary study to evaluate influence of biodiesel/kerosene mixtures on combustion temperature profile is explored. A simple cylindrical combustion chamber configuration with plain orifice atomiser is used for the evaluation. The evaluation is performed under stoichiometric air to fuel ratio. Six samples of fuels are used: 100BD (pure biodiesel), 100KE (pure Jet-A), 20KE80BD (20% Jet-A/80% Biodiesel), 40KE60BD (40% Jet-A/60% Biodiesel), 60KE40BD (60% Jet-A/40% Biodiesel), and 80KE20BD (80% Jet-A/20% Biodiesel). Results showed that the oxygen content, viscosity, and lower heating value are key parameters in affecting the temperature profile inside the chamber. Biodiesel is known to have higher energy content, higher viscosity and lower heating value compared to kerosene. Mixing biodiesel with kerosene improves viscosity and caloric value but reduces oxygen content of the fuel. High oxygen content of the biodiesel resulted to the highest flame temperature. However the flame temperature reduce as the percentage of biodiesel in the fuel mixture reduces.

1. Introduction
The evaluation of fuel properties is essential in determining the suitability of the fuel for gas turbine engines. Fuel properties are highlighted as important requirements in order to use new fuels in gas turbine engines [1]. Fuel volatility will affect combustion efficiency, ignition, exhaust temperature distribution, and safety. The increase in carbon/hydrogen (C/H) ratio is found to affect the tendency of carbon to deposit in the combustion chamber. Vapour pressure, viscosity and density are found to influence the evaporation and atomisation of the liquid fuel [2]. Fuel heating value is known to affect the amount of fuel consumed by the gas turbine and the thrust produced from the gas turbine engine [3-5]. In another study, heating value affects the gradient of flame temperature, which consequently influences the increase in nitrogen oxide (NOx) [5]. The heating value of the fuel is related to the molecular weight of the fuels. The heaviest fuels normally have the highest heating value, and thus the fuel consumption is reduced. Aside from heating value, heat capacity also contributes to the production of engine thrust [4]. The same study also observed an increment increase in fuel consumption as the density of the fuel increases.

Due to the fuel shortage crisis and the escalation of environmental pollution, a massive study on the effectiveness of using biofuel as a substitute for conventional kerosene has been performed on aircraft application [3-6] as well as other gas turbine engine that generates power [7]. However, the challenge
in using biofuel in the gas turbine engine is steep. The combustion chamber has to be redesigned to obtain higher combustion efficiency and lower NOx [8]. In aviation perspective, for the near and short-term application, biofuel has to be blended with the aviation turbine for up to 50% [9] to ensure the standard requirement so that the aviation fuel is achieved. Hydrotreated renewable jet fuel and bio-synthetic paraffinic kerosene types of fuel are suitable to be used as drop-in fuel in the aircraft engine. The capability of these fuels in generating thrust and low NOx generated from the aircraft engine is promising [3, 5, 9-11]. However, incomplete combustion, which consequently produces high carbon monoxide (CO), is observed.

Instead of powering aircraft, empowering gas turbine engine with biofuel for generating power has been imposed and reported vastly. Mustafa et al. [7] elucidated the effects of fuel-air equivalence ratios on combustion driven thermoelectric (TE) and thermophotovoltaic (TPV) power systems using several blends of vegetable-cooking oil. The use of biofuel increases CO, however, the generation of CO for TE system is found to be lower than TPV system, while the electrical efficiencies of TE and TPV system were improved at rich mixtures. The performance and emission characteristics of biofuel and biofuel blends in a 30kW gas turbine engine have been studied by Habib et al. [12]. Biofuels used in this study were soy methyl ester, canola methyl ester, recycled rapeseed methyl ester, hog-fat biofuel, and their 50% (volume) blends in Jet A. Decreases on CO and NOx pollutant have been observed with greater reduction, and they were found if blended fuel was used. Higher thermal efficiencies of pure biofuels are found owing to the presence of oxygen molecules in the biofuel. Meanwhile, Li Zhou et al. [13] performed an analysis on the influence of ethanol and methanol on the combustion characteristics and engine performance system. The study pointed out that viscosity and calorific value are key factors affecting the atomisation and combustion characteristics of the biofuels. Due to low fuel viscosity, low initial ejection temperature without preheating is necessary to obtain a better atomisation. The study found out that the mass flow rate of the biofuel needs to be increased in order to obtain the same magnitude of thrust as conventional fuel. Most of the studies above have concerned on CO generation, which associates with incomplete combustion due to poor fuel spray formation process.

Understanding the spray formation process is an important step to increase combustion efficiency and reduce pollutant emissions [14]. Fuel atomisation can be affected by many factors such as droplet velocity, spray cone angle, and spray tip penetration [15], which was influenced by the property of the fuel [15, 16] an ambient condition of the combustion chamber [6, 15, 17] as well as nozzle design [17]. Fuel with low viscosity, such as bioethanol, improves fuel evaporation and the breakup process [15]. Lujaji et al. [16] found that liquid density, heating value, and viscosity are the major contributors to spray droplet size when different liquid flow rates are set to maintain the same energy input. The higher viscosity of atomised liquid tends to create a larger droplet to minimise the growth rate of instabilities. A higher energy density causes lesser amounts of fuel exiting the nozzle and better atomisation.

A complete combustion can also be achieved by having fuel with high oxygen content such as biodiesel and vegetable oil [18]. Biodiesel contains 11% oxygen by weight [18]. The oxygen provides higher heat release during the premixed phase combustion, offers rapid breakage of hydrocarbon, and contributes to a hotter combustion process for complete combustion [19, 20]. Mustafa et al. [7] observed that fuel with high oxygen content provides advantageous post flame oxidation and flame speed during air-fuel interactions. This fuel promotes better oxidation during the combustion process and produces low CO.

Most of the works mentioned above pointed out the importance of fuel properties on NOx and CO generation. However, works prior to transient behaviour of the biofuel inside the combustion chamber are lacking and remained persistently challenging. In this paper, Jet-A, biodiesel, and biodiesel/kerosene mixtures are chosen to be tested in a simple cylindrical shape of a combustion chamber with plain orifice atomiser. Temperature profile, velocity contours and oxygen concentrations of the selected fuels are discussed and a comparison between the fuels is presented.
2. Methodology

2.1. Model Description

The study uses a simple combustion chamber with plain orifice atomiser. The length of the chamber is 310mm, air inlet and outer diameter of 70mm and 60mm respectively, and fuel inlet diameter of 10mm. The geometric model of the chamber is shown in Figure 1(a) while Figure 1(b) shows 62530 cells of non-structured mesh was performed. Table 1 shows dimension for each zone in the combustion chamber.

![Geometric model](image1)

(a) Geometric model

![Mesh](image2)

(b) Mesh

**Figure 1.** Geometric model (a) and mesh (b) of the combustion chamber

**Table 1.** Main dimension of combustor chamber

| Zone            | Flow Area (m²) | Reactor Length (m) |
|-----------------|----------------|--------------------|
| Flame front (FF)| 0.015          |                    |
| Primary (PZ)    | 0.015          | 0.019              |
| Secondary (SZ)  | 0.015          | 0.056              |
| Dilution (DZ)   | 0.015          | 0.31               |
Biodiesel has been recognised as one of the potential substitutes for conventional fuels in a combustion system. Biodiesel consists of a mixture of methyl esters derived from transesterification process of either vegetable oils [21], recycled waste, or animal fats [22]. Thermal stability issues and the tendency of biodiesel to freeze at normal cruise temperature make it inappropriate to be used in aircraft engine [23], but it has been successfully used as blends with diesel in compression-ignition engines [24].

Six samples of fuels are used: 100BD (pure biodiesel), 100KE (pure Jet-A), 20KE80BD (20% Jet-A/80% Biodiesel), 40KE60BD (40% Jet-A/60% Biodiesel), 60KE40BD (60% Jet-A/40% Biodiesel), and 80KE20BD (80% Jet-A/20% Biodiesel). The chemical properties of the fuel mixtures such as density, kinematic viscosity, flash point and heating value of the fuel mixtures were measured experimentally. However due to limitation of the equipment available in the lab, specific heat capacity, surface tension, latent heat of vaporisation, vaporisation temperature, and boiling point were predicted using Equation 1.

\[ X = aA + bB \]  

where \( X \) is fuel properties of the mixtures, \( a \) and \( b \) is the percentage of kerosene and biodiesel respectively (%), while \( A \) and \( B \) are the properties of kerosene and biodiesel obtained from literature respectively. Density of the fuel mixture was determined according to ASTM D1298 using a hydrometer and a water bath. The density was measured from 30 °C to 80 °C. Kinematic viscosity of the fuels is obtained by dividing dynamic viscosity with density (Equation 2).

\[ \nu = \frac{\mu}{\rho}, \]  

where \( \nu \) is kinematic viscosity (\( \text{mm}^2/\text{s} \)), \( \mu \) is dynamic viscosity (kg/mms), and \( \rho \) is density of fuel (kg/mm\(^3\)). Dynamic viscosity of the fuels is measured according to ASTM D445 using Brookfield DV-III Ultra’s viscometer. The dynamic viscosity is measure for temperature ranging temperature ranging from 30 °C to 80 °C.

An elemental analyser (Perkin Elmer 2400 CHN Element) was used to analyse the chemical components contain in 100BD. Results obtained from the analysis were used to predict the chemical components of the fuel mixtures by using Equation (3).

\[ C = (D \times a) + (E \times b) \]  

where \( C \) is the number of carbon/hydrogen/oxygen in fuel mixtures, \( a \) is percentage of kerosene in the mixtures (%), \( b \) is percentage of biodiesel in the mixtures (%), \( D \) is number of carbon/hydrogen in kerosene, and \( E \) is number of carbon/hydrogen/oxygen in biodiesel. Table 2 summarises the properties of the fuel mixtures used in this study.

In evaluating the fuel mixtures, user defined function (UDF) was used due to unavailability of the properties of the fuel mixture in the CFD library. Properties of the fuel as listed in Table 2 will be used as input into the UDF.

2.2. Simulation Method

Temperature profile of all tested fuels in the designed combustion chamber is assessed at stoichiometric, lean, and rich air to fuel ratio. The simulation was performed by assuming the combustion to be non-premixed while the flow was taken as steady and incompressible. Temperature and pressure of the combustor was set to be room temperature and atmospheric pressure respectively.
Table 2. Summary of Fuel Properties for Different Fuel Samples Measured via Experimental setup or Prediction

| Properties                  | 100KE | 20KE/80BD | 40KE/60BD | 60KE/40BD | 80KE/20BD | 100BD | Measurement method |
|-----------------------------|-------|-----------|-----------|-----------|-----------|-------|-------------------|
| Density (kg/m³)             | 795   | 850       | 840       | 830       | 810       | 860   | ASTM D1298        |
| Specific Heat Capacity (J/kg.K) | 2090 | 1966.8    | 1948.32   | 1954.48   | 1960.64   | 1936*| Prediction       |
| Dynamic Viscosity (kg/ms)   | 0.001 | 0.004     | 0.0025    | 0.002     | 0.0015    | 0.0055| Prediction       |
| Surface Tension (N/m)       | 0.0263| 0.0253    | 0.0251    | 0.0252    | 0.0252    | 0.025*| Prediction       |
| Latent Heat of Vaporization (MJ/kg) | 226  | 237.2     | 234.4     | 231.6     | 228.8     | 240*  | Prediction       |
| Vaporization Temp (K)       | 341   | 574.6     | 516.2     | 457.8     | 399.4     | 633*  | Prediction       |
| Boiling Point (K)           | 477   | 579.4     | 553.8     | 528.8     | 502.6     | 605*  | Prediction       |
| Caloric value (MJ/kg)       | 30.6  | 31.5      | 32.0      | 34.4      | 35.4      | 42.6  | ASTM D4809       |
| Molecular Formula           | C₁₂H₂₃ | C₁₀H₁₃O₂ | C₁₁H₁₃O | C₁₁H₁₃O | C₁₂H₂₅ | C₁₀H₁₃O₂ | Prediction |

*Reference Value [25]

Boundary condition was set according to Eq. (3) to Eq. (5). The boundary condition was defined by assuming constant power generated from the combustion. Fuel mass flow rate was calculated using Eq. (3) by taking into account the relationship between the power generated through combustion, and the caloric value of the fuel samples. The caloric value of the tested fuels used for mass flow rate calculation was obtained from the test experiment conducted earlier. The velocity of the fuel was calculated using Eq. (4) by assuming that the system is incompressible. The oxidizer (air) inlet rate was calculated using Eq. (5) by multiplying the fuel rate with the respected air to fuel ratio. The turbulent density and turbulent viscosity ratio were both set as 5%. Details of the parameters used in the evaluation are shown in Table 3.

\[
\dot{m}_f = \frac{P}{C_v} \quad (3)
\]

\[
V_f = \frac{\dot{m}_f}{\rho \times A} \quad (4)
\]

\[
V_o = V_f \times AFR \quad (5)
\]

where \(\dot{m}_f\) is fuel mass flow rate (kg/s), \(V_f\) is fuel velocity rate (m/s), \(V_o\) is oxidiser velocity rate (m/s), \(P\) is power (0.6MJ/s), \(A\) is fuel inlet area (0.0000785 m²), \(C_v\) is caloric value (MJ/kg), \(\rho\) is fuel’s density (kg/m³) and AFR is air to fuel ratio.

Table 3. Inlet Boundary Condition for Fuel and Oxidizer at Stoichiometric, Lean and Rich AFR

|                   | 100KE | 20KE/80BD | 40KE/60BD | 60KE/40BD | 80KE/20BD | 100BD |
|-------------------|-------|-----------|-----------|-----------|-----------|-------|
| Fuel Mass Flow Rate (kg/s) | 0.014 | 0.019 | 0.0187 | 0.017 | 0.0169 | 0.0196 |
| Fuel Velocity Rate (m/s)  | 0.223 | 0.287 | 0.285 | 0.268 | 0.267 | 0.290 |
| Air-Fuel Ratio       | 15.6  | 13.92 | 14.34 | 14.76 | 15.18 | 13.5  |
| Air Velocity Rate (m/s) | 3.479 | 3.976 | 4.080 | 3.955 | 4.047 | 3.917 |
3. Results and Discussion

3.1. Temperature distribution of the fuel mixtures along the chamber

Temperature profile of the designed combustion chamber is predicted for all the fuel mixtures. The effects of the fuel mixture were analysed for three different cases: stoichiometric, lean and rich air to fuel ratio. The analysis was performed under non-premixed combustion, incompressible flow, under room temperature, and at atmospheric conditions. Desired power output generated through combustion is assumed constant to identify the influence of fuel properties during combustion. An equivalence ratio of one (1) was used for stoichiometric, the equivalence ratio of 0.7 was used for lean and the equivalence ratio of 1.5 was used for rich.

The distribution of temperature for all the tested fuels at stoichiometric, lean and rich fuel-air equivalence ratio test cases is illustrated in Figure 2, Figure 3, and Figure 4 respectively. From the figures, it can be seen that the combustion took place at the upstream of the combustion section. The temperature reduces and getting constant downstream. Figure 5 shows comparison of flame temperature for all fuels at different test cases. It is noticed that for all type of fuels, maximum temperature is observed at stoichiometric ratio where the both fuel and air has ideal ratio in order to burn completely without having excessive air. Temperature of the flame is lower at rich while at lean the lowest flame temperature is observed. At stoichiometric, 100BD is observed to have the highest flame temperature compared to other fuels. The presence of oxygen in biodiesel was found to be a factor to the highest flame temperature. Oxygen content in 100BD promoted to the higher heat release during the combustion, and thus it resulted to the higher gas temperature in the combustion chamber. The result was consistent with Palash et al. [26] and Mustafa et al. [7], who observed the similar behaviour for the oxygenated type of fuel. Additionally, the flame temperature reduced as the percentage of kerosene in the mixture increased due to the reduction of oxygen molecules in the mixture.

In addition, the highest flame temperature of 100BD is due to the amount of fuel injected into the combustion chamber. As in this study, all fuels are assumed to generate same power output as 100KE. Since LHV of 100BD is lower than 100KE, more fuel has to be injected thus produce higher combustion temperature.

![Figure 2](image-url)
3.2. Comparison of flame temperature at different combustion zones

Figure 6 to Figure 8 show the comparison of flame temperature at different combustion zones as defined in Table 2. For all test cases, the highest flame temperature is observed to be located at the secondary zone of the chamber. It is worth to mention here that the effect of cooling air is not counted in this study. Therefore highest temperature in this region is expected. In the real combustion chamber, an amount of air will be extracted from compressor bleed to be entered into secondary and dilution zone. This air is used to ensure the turbine section can tolerate high temperature that exit from combustion chamber.

Meanwhile, at PZ, 100KE is found to have the highest flame temperature compared to 100BD. This is because of the lowest boiling temperature of the fuel which eventually provides faster vaporisation process will be able to mix with air homogenously for combustion. Similarly due to highest boiling temperature, 100BD requires longer time to fully evaporate thus only be able to fully combust in SZ. As a result, higher temperature is observed at DZ which consequently requires more cooling air is required to be extracted from compressor bleed.

![Figure 3](image-url)

**Figure 3.** Temperature of the tested fuels at Primary, Secondary and Dilution zones for Stoichiometric

4. Conclusion

Five blends of BD – JP4 blended fuels: 20KE80BD, 40KE60BD, 60KE40BD, and 80KE20BD were tested in a simple cylindrical shape of the combustion chamber with plain orifice atomiser at stoichiometric air to fuel ratio. The combustion characteristics were discussed in terms of temperature aspect. The effects of fuel properties on combustion characteristics of the tested fuels were observed. Combusting 100BD produces the highest flame temperature compared to other fuel mixtures. The temperature reduces as the percentage of biodiesel in the mixtures reduces. High oxygen content in biodiesel promotes the oxidation process during combustion, and thus it increases the flame temperature. Additionally due to lower LHV of 100BD, more fuel has to be injected in order to maintain the similar power output as 100KE. As a result the highest flame temperature is observed. 100BD also has highest boiling temperature and more volatile compare to the other fuels. Consequently, 100BD requires more time to evaporate completely and finally burnt at SZ. As a result 100BD provides highest temperature at DZ, therefore requires more cooling air to be extracted from compressor bleed to reduce the temperature.
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