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Modelling the performance of aero-gas turbine engine using algae-based biofuel with emission prediction

Muhammad Hanafi Azami[1], Muhamad Zaki[2], Mark Savill[3], and Yi-Guang Li[4]

[1,2]Department of Mechanical Engineering,
Kulliyyah of Engineering, International Islamic University Malaysia
[3,4]Centre for Propulsion Engineering,
Cranfield University, United Kingdom

Corresponding author e-mail: hanafiazami@iium.edu.my

Abstract. The world oil consumption is at the peak where the fuel price is insubstantial and can increase dramatically due to economic, social, and political factors and unprecedented stability. Since fuel resources are scarce, it is an urgent need to find alternative fuel. Biofuel is one of the favorable choices in the market. Algae-based biofuel is the fourth generation of biofuel where it does not compete with the food production and it has myriad of advantages. These abundant algae are easy to cultivate and researchers found that algae-based biofuel is capable of reducing engine emission. This paper modelled the RB211 aero-gas turbine engine by utilizing algae-based biofuel with various blended percentage ratios at different flight conditions. Cranfield's University in-house software, PYTHIA, and HEPHAESTUS are used to model the engine performance and emission prediction respectively. PYTHIA programme uses a modified Newton-Raphson convergence technique in the zero-dimensional steady-state model for both design and off-design conditions. Meanwhile, HEPHAESTUS software uses the Zeldovich equations (for NOx) and models the emission by implementing a partially-stirred reactor (PSR) model and perfectly stirred reactor (PSRS) models at different zones in the combustor. Results have shown that thrust force produced is increasing at higher blended percentage ratio of algae biofuel. Through emission analysis prediction, generally, the nitrous oxide emission formation is lower at a higher altitude during the cruising. Results also predicted that higher percentage blended ratio of algae biofuel also reduces the emission formation.

1. Introduction

Nowadays, the technology advancement in aircraft engine have experienced a dramatic increase. Engineers are studying on how to improve the performance of the engine and make it better every day. The most interesting topic that engineers and also citizens care about is fuel efficiency and emission caused by transportation. In about 10 years to the future, we will see about 15-20 percent improvement in fuel efficiency. A study by Daggett [1] on fuels in commercial aircraft said that "air travel growth is predicted to continue at 5 percent per year". This means that the future fuel efficiency will be outpaced by increasing amount of fuel needed in aircraft industry. Thus, we can predict the oil peaking will occur one day and we have less energy resources available to use.

Aircraft emission also responsible in rising concentration of greenhouse gases (GHGs) in the atmosphere. It is reported by Anger [2] that aviation industry produces carbon dioxide emission that cover about 3% of global emission in 2004. Literally the number is small, however the European environment Agency [3] reported that carbon dioxide emission from aviation in European countries showed a massive growth from 1990 to 2004, about 85%. These two data concluded that number of emission every year keep increasing and should be a future concern. Besides, emission from aircraft engine also include nitrogen oxides, sulphur dioxide, soot and carbon monoxide. Anger [2] added that, emissions from aircraft engine that are less well understood is the formation of cirrus cloud and contrails. Cirrus cloud are in form of high level clouds and have greenhouse effect and solar albedo effect [4]. Contrails are line shaped clouds form that are visible from the movement of aircraft in air. The impact of contrails is quite similar to impact by carbon dioxide emission, reported by Penner[5]. It is understood, that current aircraft condition is in need of sustainable energy for future use that are renewable and produce low emission.

In these generation, the research on biofuel as alternative fuel has been an interesting discussion among researchers. Biofuels or plant derived fuel offer a wide variety of selection such as soybean oils, rice bran oil, palm oils, corn, algae and many more. This allows us to do various kind of experiment to test the effectiveness of this biofuel. The most promising biofuel as an alternative fuel is algae. It grows abundantly and does not require agricultural land. Algae has huge supply and could be the future fuel for aircraft operation as research also find that this biofuel could reduce emissions in aircraft operation. The most common type of algae is green algae (chlorophyta), red algae (rhodophyta) and brown kelps (Phaeophyta). Based on a research by He [6], green microalgae is more suitable for biofuel production due to high lipid content than other type of microalgae. It has about 25% wt lipid content and high lipid content could improve the efficiency of biomass processing. It is also important to note that green algae are mostly freshwater species. Brown microalgae has high carbohydrate content and high ash content. Thus, brown microalgae is not good for biodiesel production and more suitable for fermentable sugar production.

Biofuels that are developed for aircraft applications are called “biojet” fuels. There are several challenges in using this biojet such as its tendency to freeze at normal operating flight temperatures until recent development improved this. Other major challenge is this biofuel has poor high temperature thermal stability characteristics. The biofuel need to blend with major percent of aircraft fuels (jet-A).

This research is focusing on modelling gas turbine engine in various conditions. This include varying fuel mixture and fuel type. Thus, software chosen to simulate the result must be able satisfy this requirements and user friendly. PHYTIA software is selected as it can be used to stimulate engine performance and considered to have user friendly interface and been tested for many years in validation of numerous gas turbines [7]. The data obtained from this software is thrust, specific fuel consumption and others. In emission modelling, HEPHAESTUS software will be used as it uses the same data from PHYTIA and can predict emissions from biofuel with ease [8]. The main data required from PHYTIA software is emission index EINOX.

2. Methodology

The PHYTIA program was selected for computational analysis. Igie [9] stated that this program can design and measure numerous gas turbine engines for both design and off-design points using a modified Newton–Raphson convergence technique in the zero-dimensional steady-state model. PHYTIA is integrated with TURBOMATCH code to solve iterations in mass equation and energy balance for engine component selected [8].

$$\frac{W_n\sqrt{T_n}}{P_n} = \frac{W_{n+1}\sqrt{T_{n+1}}}{P_{n+1}} \tag{1}$$

$$Turbine\ Work\ (TW) = Compressor\ Work\ (CW) \tag{2}$$

Then, the data obtained are imported to the excel spreadsheet for data analysis as shows in Figure 1. PHYTIA is considered to have user friendly interface and been tested for many years in validation of numerous gas turbines [10]. The latest update on PHYTIA enable it to change the fuel type and diversify the blended mixing ratio percentage while using same engine selection for the kerosene case [11]. This enables deeper research on fuel usage for engines in different operating condition.

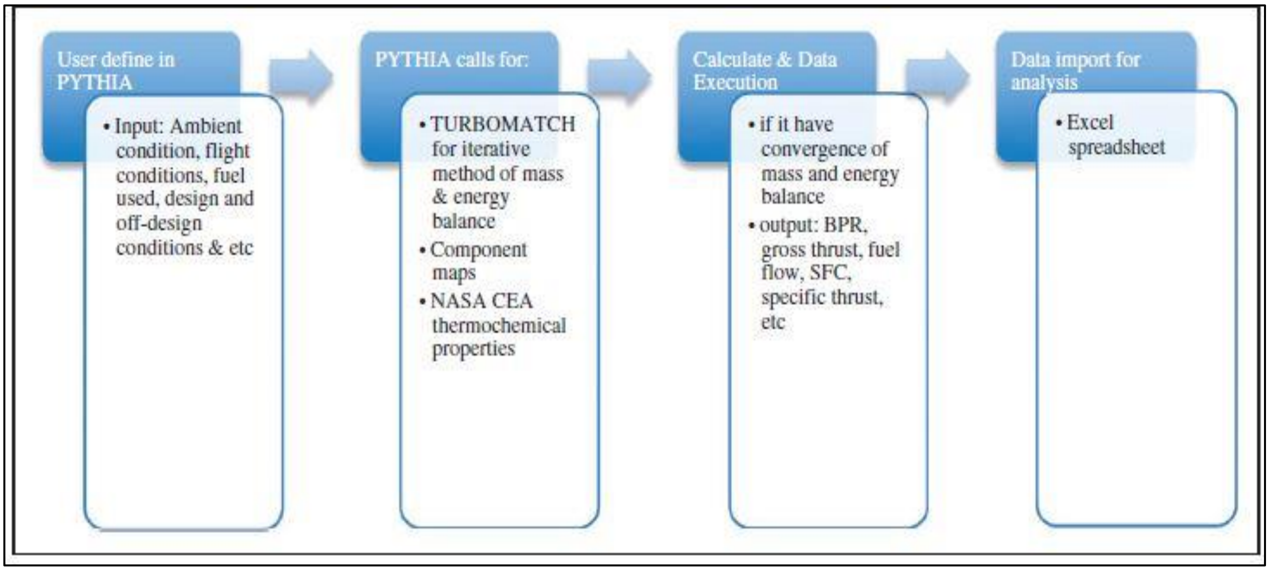

Figure 1. PHYTIA process flow chart. [8]

Software HEPHAESTUS are used in emission analysis for this research as it can predict carbon monoxide and nitrous oxides emissions at multiple flight conditions. This software required data that were obtained from PHYTIA. The parameter required for the software input are fuel total temperature, ambient conditions, air total pressure and temperature at the combustor inlet, fuel and total air mass flow rate. Emission prediction technique used to validate the data obtained by HEPHAESTUS is called correlation-based models. It is among the simplest method to predict the emission, however it require large number of data from the engine/combustor. Primary variables such as pressure and temperature are obtained from PHYTIA.

3. Result and discussion

Figure 2 shows that the thrust increase along with the increase of blended ratio percentage at the altitude of 2000m. At higher Mach numbers of 0.6 and 0.8, the difference in thrust has increases significantly as blended percentage ratio increases. In terms of specific fuel consumption, SFC which is used to describe the fuel efficiency of an engine design to thrust output. SFC for gas turbine is the mass of fuel needed to provide the net thrust for a given period. With the same flight conditions and engine configurations the SFC can be identified. Figure 3 shows the SFC trends and the percentage difference of SFC with Mach number. Unfortunately, the SFC has increase at higher percentage blended ratios. This shows that the algae-based biofuel consumed more fuel compared to kerosene fuel.

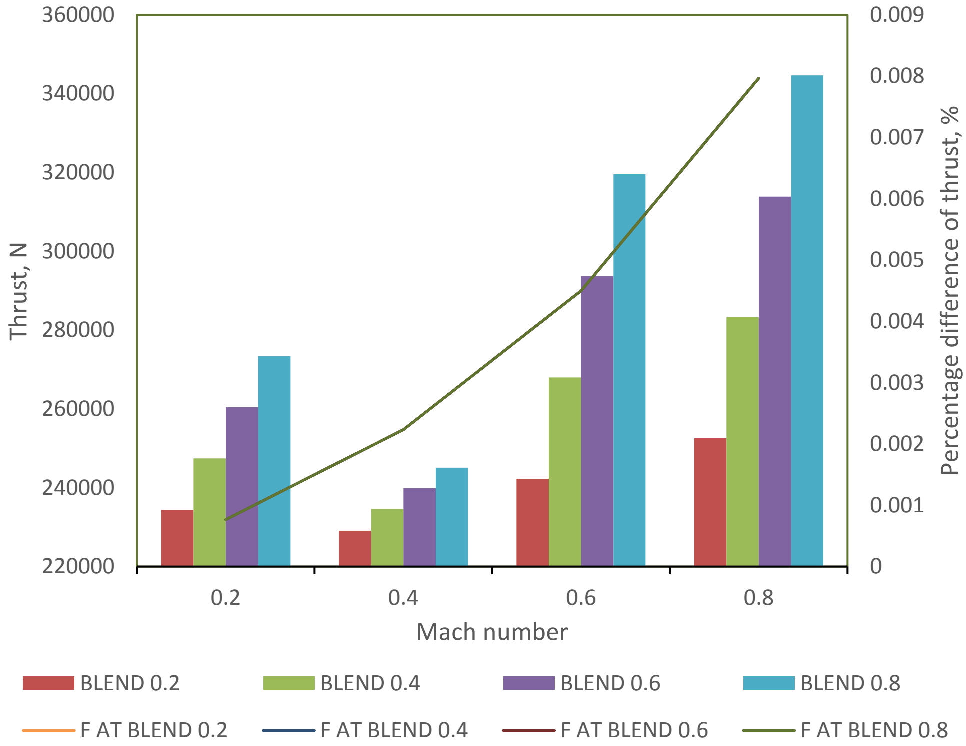

Figure 2. Thrust vs Mach number with respect to blended ratio at altitude 2000

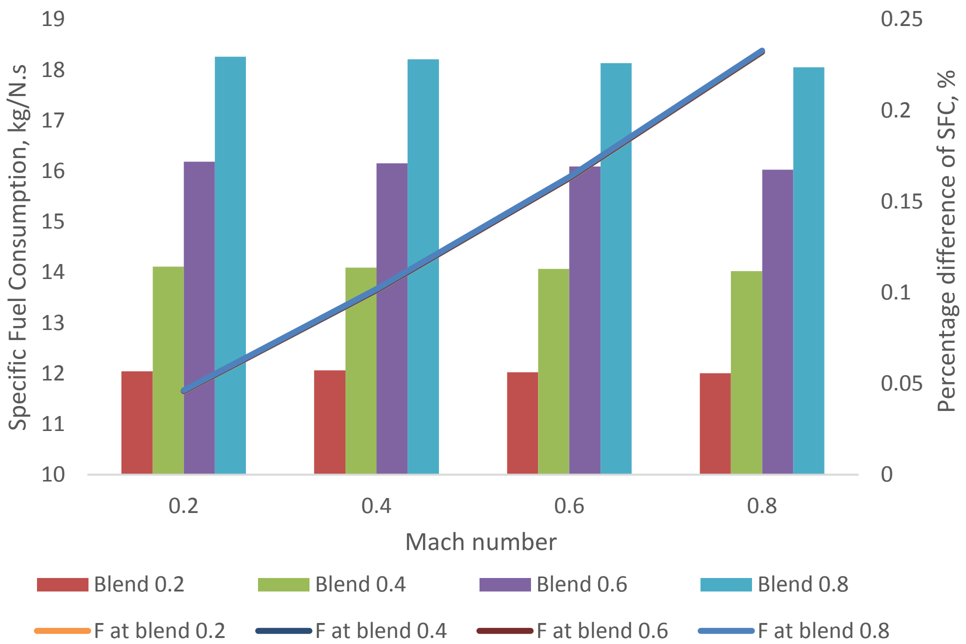

Figure 3. Specific fuel consumption (SFC) Vs Mach number with respect to blended ratio at altitude 2000

Prediction of engine NOx emission is complex and it is measure in term of NOx emission index (EINOx). Emission model prediction from HEPHAESTUS are compared with published correlation based models such as Lipfert and Lefebvre correlations. The results are tabulated in Table 1. According to Chandrasekaran [12], Lipfert correlation over predict EINOx value for all gas turbine engine analyzed. This means that the value is a little bit diverged from other data but still in the acceptable range. In addition, the percentage difference between HEPHAESTUS value and the two correlation stated is under 10%. Thus, it can be assumed that the EINOx value from HEPHAESTUS is accepted and is the main data.

Table 1. EINOx analysis at Mach 0.4 at altitude 2000

Blended ratio (%)	Lipfert and % difference with HEPHAESTUS	Lefebvre and % difference with HEPHAESTUS	Hephaestus (g/kg fuel)
0	52.79 (7.68%)	56.88 (0.54%)	57.19
100	52.81 (6.78%)	57.47 (1.47%)	56.65

It shows that the HEPHAESTUS has an acceptable trend, and the capability of HEPHAESTUS has been extended to predict the nitrous oxide emission at various altitudes. Figure 4 shown that the EINOx of algae-based biofuels has much lower EINOx and the trend is decreasing at higher altitude. It is believed that EINOx trend is reduces in algae-based biofuel due to the lower flame temperature of the fuel. EINOx is highly sensitive to temperature as well as pressure. In PYTHIA, we observed that the combustion chamber temperature is much lower using algae-based biofuel.

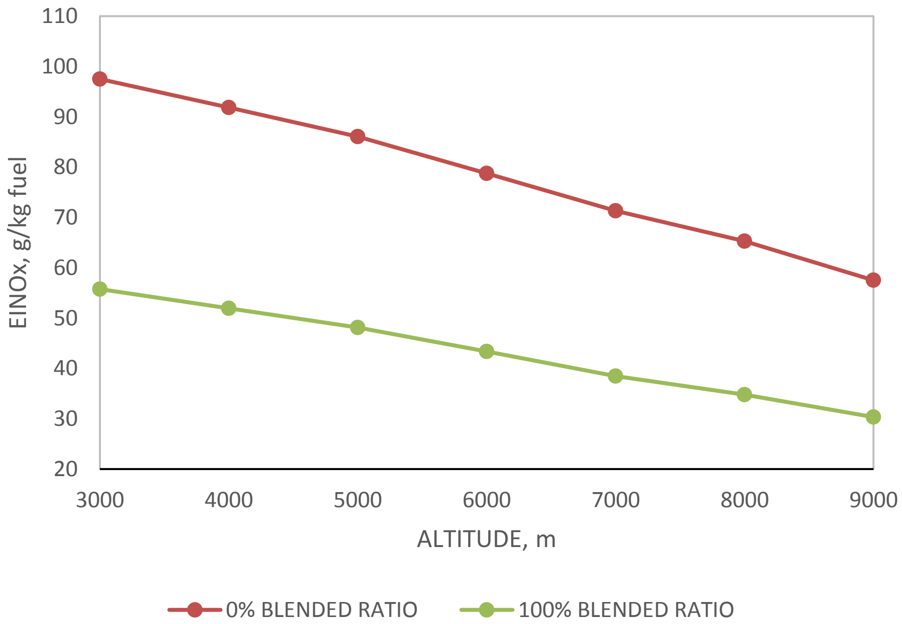

Figure 4. EINOx at cruise speed vs altitude with respect to KE+AG blended ratio

4. Conclusion

The effect of different blended percentage ratio of algae-based biofuel to performance and emission of gas turbine are determined. Results shown that the thrust force is increasing at higher blended percentage ratio. However, the SFC also tends to increase as well. This might be the disadvantage. For the emission analysis prediction, shown in HEPHAESTUS, the nitrogen oxide emission index can be reduced using algae-based biofuel.

Acknowledgement

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