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Modelling the performance and emission prediction of RB211 aero-gas turbine engine fuelled by Jatropha-based biofuel

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Abstract. Fossil fuel is one of the world vital energy resources. The development of transportation technologies increases the demand for petroleum derivative globally. Fossil fuel consumption produces emissions, which potentially harm the environment and human health. Many mitigations have been implemented to address the two main crises; the energy scarcity and environmental calamity. This paper will discuss on one of the potential solutions by analyzing the performance and emission prediction of aero-gas turbine engine fuelled by Jatropha-based biofuel. Performance analysis was made based on the thrust and specific fuel consumptions at different blended ratio percentages for various flight conditions. The three-shaft high-bypass-ratio engine model, which is identical to the Rolls Royce RB211-524 was used to model in an in-house Cranfield's University software, PYTHIA. PYTHIA is integrated with the TURBOMATCH performance evaluation programme by iterating the mass and energy balance for each engine component. The analysis is then continued to predict Nitrogen Oxides emission index (EINOx) at every flight conditions using an in-house Cranfield's University computer tool, HEPHAESTUS. HEPHAESTUS is an emission prediction software by using Zel'Dovich 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. Validation showed that HEPHAESTUS is able to capture a reasonable prediction as compared to the International Civil Aviation Organization (ICAO) databank. The performance the biofuel has shown an improvement in engine performance at higher percentage blended ratio but also increase the nitrous oxide indices emission slightly.

1. Introduction

Fossil fuels are highly demanded globally. Burning the fuel is one of the oldest methods for generating energy and power all around the world. Fossil fuels (oil, natural gas, and coal) contribute to approximately 80% of total world energy supply [1]. The World Energy Outlook (WEO) 2007 claims that in 2030, it is expected that the energy demand will grow up to 84% as the fossil derivative will remain to be the major source. By 2030 fossil fuel is predicted to amplify the quantity up to 61 million barrels per day from 36 million barrels per day in 2006 [2]. The amount of all three types of fossil derivative escalate as the time increases. Besides, the demands on oil are always the highest, while the demands on coal are greater than gas. Consequently, the consumption of fossil fuels has grown over the last 40 years and is expected to follow the same trend in the future.

The world fossil derivative resources are estimated to reach the peak between 2013 and 2020 [3]. Through the formalisation of the depletion of fossil fuel rate curves, it is a hesitate to believe that the symmetrical bell curve is the last resort in predicting the completion of the fossil derivative lifespan [4]. The example of the country that has found the fossil fuel production peak has already been reached is Turkey. Turkey has indicated that their fossil derivative will diminish in 2038 [5]. This shows that the fuel reserve is depleting rapidly as the global demand hike up. Moreover, fossil fuel utilization also produces emissions that can contribute harm towards the health at the human population level as well as the environmental concerns. The Kingdom of Saudi Arabia reported its emissions of CO_2, CH_4, and N_2O from road transportation based from fossil fuel in 2000 are approximately 56 million tons, 10.42 thousand tons, and 0.47 thousand tons, respectively [6]. In 2010, the estimated emissions of CO_2, CH_4, and N_2O are approximately 98.12 million tons, 18.19 thousand tons, and 0.83 thousand tons, respectively. In 2020, the forecasted emissions of CO_2 are expected to be 163.33 million tons, CH_4 are expected to be 32.72 thousand tons and N_2O are expected to be 1.39 thousand tons [7].

Biofuel can be derived from biomass for instance vegetable oils such as palm oil, rapeseed oil and others [8]. The raw materials for the preparation of biodiesel can be classified into three types: (i) Vegetable oils; (ii) Waste frying oils and (iii) Animal fats. The main superiority of biofuel is that an existing internal combustion engine can operate directly by utilizing it without major modifications. Jatropha biofuel is one of the alternatives solutions towards rapid depletion of fossil derivatives due to Jatropha can be reproduced in a short period of time. Therefore, it can potentially reduce the global dependence on fossil derivatives. Meanwhile, as in environmental concern, the production of Jatropha biodiesel releases less greenhouse gas (GHG) emissions as compared to conventional fossil derivatives. Alongside, the biofuel can be reproduced over a short period, the prediction has shown that the use of Jatropha biofuel can abbreviate the greenhouse gas emissions up to 23% from the conventional fossil derivative [9]. Furthermore, Jatropha Curcas plantation is very economical as it natures of scarcity crops. With a little quantity of moisture, it can grow on rough land and can keep producing up to 40 years [10]. Jatropha crops also need no fertilizers, crop rotation. no insecticides also required. has the lowest cost compared to other biomass feedstocks, and inedible plant. This shows that Jatropha-based biofuel can potentially be a source of renewable energy and as an alternative to conventional fossil derivative while simultaneously reduce harm on the environment. For this reason, an engine modelled fuelled by Jatropha-based biofuel is studied. The research is directed towards the modelling of the performance and emission in a conventional aero-gas turbine engine (Rolls Royce RB211-524).

2. Methodology

The Jatropha Curcas based biofuel will be analysed as pure Jatropha biofuel, pure kerosene and also blended Jatropha-Kerosene at 20%, 40%, 60% and 80% percentage blended ratio. Continental Airlines, Air New Zealand and Interjet are among the airlines' companies that used Jatropha as the alternative fuel. A model of a 3-shaft high-bypass-ratio engine RB211-524 was used. For simulation and computational analysis, an in-house Cranfield's University software named PYTHIA program is used. Aero-gas turbine engine model and gas path analysis in PYTHIA apply a modified Newton-Raphson convergence technique. In addition, it can fill in as indicative apparatus for disintegration evaluation for off-design conditions. TURBOMATCH is a coded program that is incorporated with PYTHIA. PYTHIA has an interactive interface which requires user input then it calls for TURBOMATCH for the iteration and matching each engine components through mass and energy balance equations.

The advantage of the new version of PYTHIA program is that it is capable to vary the running fuel type as well as blending two different type of fuel with the variation of blended ratio percentages. Therefore, this work could be therefore served as an expansion of [11] work using an earlier version of PYTHIA which could only provide strict comparisons for different pure fuels for single design conditions only. Rolls Royce RB211-524 aero-gas turbine engine model is chosen in the PYTHIA's library. At a design point, kerosene fuel was selected. Each component of the engine model is described in terms of a 'brick' which has its own functionality. The details of the 'bricks' can be found in [12]. The sequential diagram of PYTHIA process can be found in [12]. It begins with the user defining inputs as previously mentioned in PYTHIA. TURBOMATCH is called for the iterations in mass equation (1) and energy equation (2) balance relation. Equations (1) and (2) should be satisfied between successive components.

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

$$Turbine\ Work\ (TW) = Compressor\ Work\ (CW) \quad (2)$$

The empirical method is often used to predict Nitrogen Oxides, NOx. The parameter of an aero gas turbine NOx emission can be determined through its emission index (EINOx). Some of the empirical correlations used in the literature in [13]. For simulation and computational analysis, this research uses in-house computer software which is called HEPHAESTUS program. It begins by inserting a few input data gained from PYTHIA software in combustor brick. The parameters that are obtained from performance PYTHIA simulation part and necessary for the simulation are ambient (flight) altitude, ambient temperature, air total temperature, air total pressure, total air mass flow rate and fuel mass flow rate. While others parameter that has been fixed based on the specifications of the Rolls Royce RB211-524 aero gas turbine as in [11].The forecasted emissions simulation is for pure kerosene, pure Jatropha and blended Jatropha and kerosene. Even though HEPHAESTUS is capable to forecast many biofuels emissions easily, only EINOx are focused for this paper.

3. Results and Discussion

The Rolls Royce RB211-524 aero gas turbine model designed in PYTHIA was validated by comparing with [7] experimental work earlier. The test was successfully conducted on Air New Zealand airline by running 50% Jatropha and 50% Jet-A fuel on Boeing 747-400 [14]. Figure 1 shows the performance in term of thrust at different flight speeds for five different blended ratio percentages of Jatropha biofuel and kerosene. Generally, all blended ratio of KE+BJ biofuel recorded an increase in thrust. The result indicates that blended Jatropha biofuel can improve the performance of aero gas turbine in thrust up to 0.47%(at 100% blended ratio and 0.4 Mach number). Meanwhile, Figure 2 shows the performance in term of Specific Fuel Consumption(SFC) at different blended percentage ratio. The results recorded a reduction of SFC at higher blended percentage ratio. It indicates that blended Jatropha-based biofuel can improve the performance of aero gas turbine in SFC reduction up to 2.69%(at 100% blended ratio and 0.8 Mach number).

Nitrous oxides formation has a complex chemical reaction. Some of empirical methods and correlation are normally used for predicting NOx in term of NOx emission index (EINOx). There are 8 correlations can be compared, which are, LIPFERT, AECMA, GASTURB, LEFABRE, BLAZOWSKI, NASA, and NPSS. The correlations can be found in [13]. Figure 3 predicts the variation of NOx emissions using different correlations at different blended ratio percentages. The HEPHAESTUS program recorded an increment in EINOx as the blended ratio moves towards pure biofuel (highest blended ratio). It is shown that HEPHAESTUS prediction falls within the range of all 8 correlations for prediction EINOx method, thus, HEPHAESTUS prediction is acceptable.

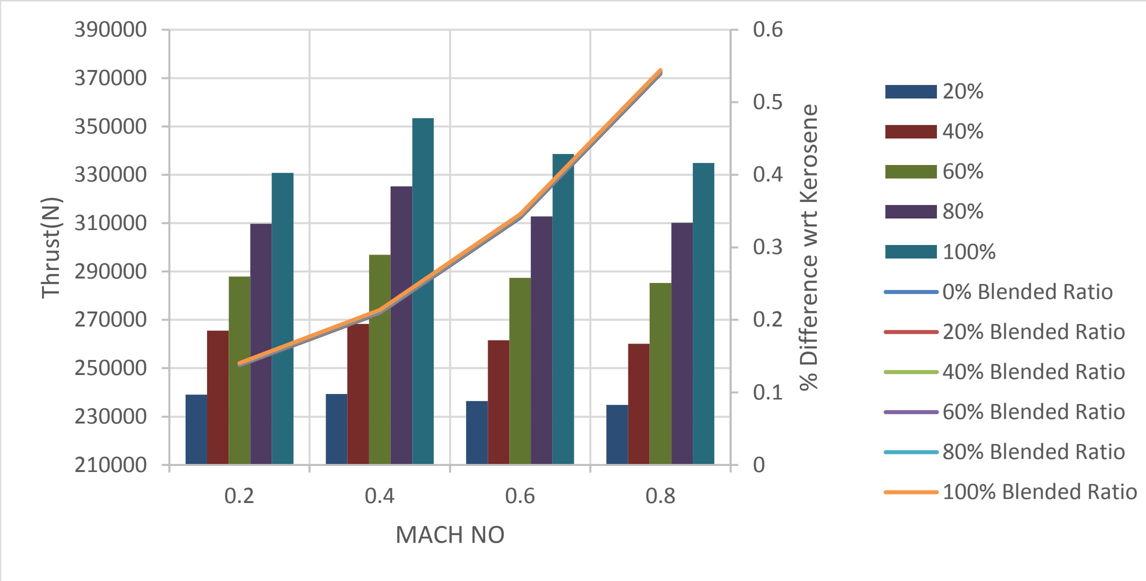

Figure 1. Thrust VS Mach Number

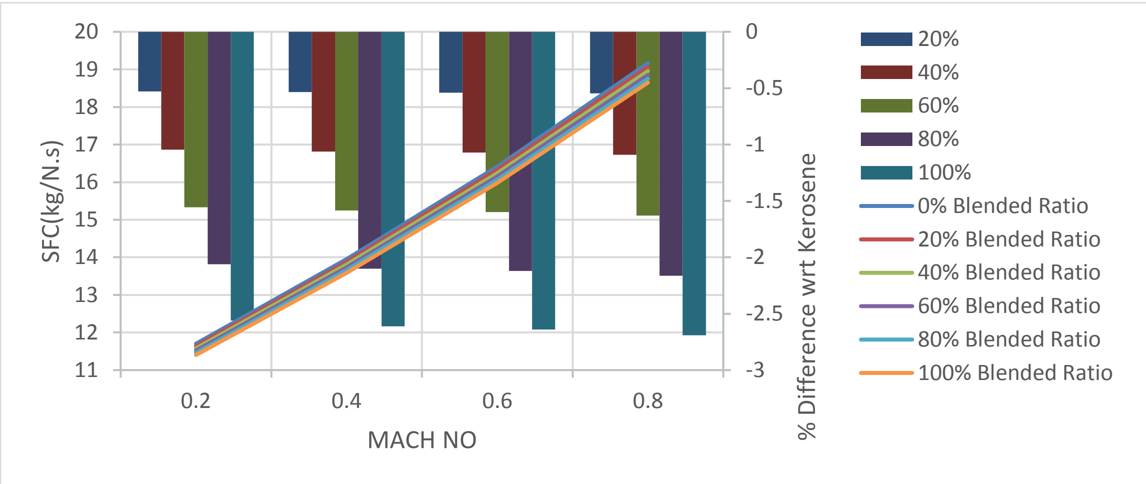

Figure 2. Specific Fuel Consumption VS Mach Number at take-off condition.

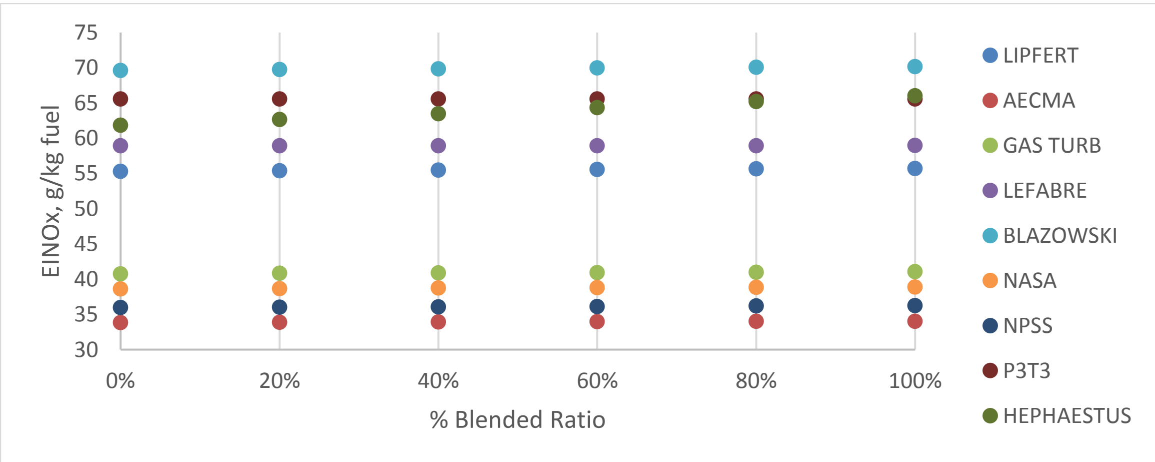

Figure 3. EINOx vs Blended Ratio at Take-off condition

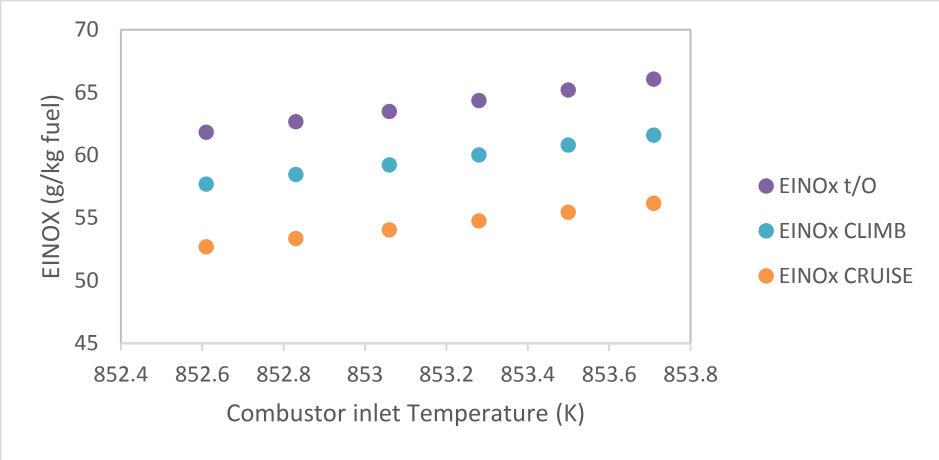

Figure 4. EINOX (g/kg fuel) vs Combustor Inlet Temperature (K)

Figure 4 shows emissions prediction using HEPHAESTUS at various flight conditions. Generally, all flight condition of KE+BJ biofuel has the same pattern which recorded an increment in EINOx due to the increase in combustor inlet temperature. Take-off flight condition resulted in a high amount of NOx due to throttling and burning more fuel. High temperature resulted in more NOx formation. NOx formation is highly dependent on the temperature.

4. Conclusion

In conclusion, Jatropha-based biofuel has been proved to be one of the most potential crops in biofuel industries. The simulation using PYTHIA software has shown that Jatropha biofuel can improve aero gas turbine performance in term of thrust and specific fuel consumption reduction up to 0.47% and 2.69% respectively. Furthermore, modelling of the Nitrogen Oxides emission index (EINOx) prediction of aero-gas turbine utilizing Jatropha biofuel successfully conducted using HEPHAESTUS codes.

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