Comparison of aircraft engine performance and emission analysis using alternative fuels

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Abstract: Following the successful flights of many commercial aircraft running with alternative fuels, the present study focuses on aircraft engine performance and emission analysis. The analysis of aircraft engine performance (thrust, fuel flow and specific fuel consumption) for different blended mixing ratio percentages of biofuels (Camelina and Jatropha) with Jet-A, at different flight conditions using in-house computer software codes, PYTHIA and TURBOMATCH. Emission analysis utilised HEPHAESTUS in-house software to predict nitrous oxides and carbon monoxide emission at various flight conditions. A model three-shaft high-bypass-ratio engine, similar to the RB211-524, was used. Blended fuels exhibited a slight improvement in engine performance at higher mixing ratio percentages; with Jatropha biofuel surpassing Camelina biofuel in terms of all considered performance indexes. Nitrous oxides can be reduced using pure Jatropha biofuel as compared to kerosene fuel for every flight condition. However, for carbon monoxide emission strongly depends on the combustor inlet conditions and flight phases.

Keywords: Camelina biofuel; emissions; engine performances; Jatropha biofuel.

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1 Introduction

In the modern era, airplanes are the preferred mode of transportation especially for long distance since it is safer and much more frequent. The demands have urged the airline industries to grow expansively. However, this growth embraces myriad problems, economically and environmentally. There are two main concerns that need to be addressed: energy crisis and environmental crisis. For instance, oil demand will hike and the fuel price reaches a peak, while the pollutant generations emitted into the atmosphere are not easily controllable which results in greenhouse gas (GHG) effects.

The world would need 50% more energy in 2030 than today as reported by the International Energy Agency (IEA) (Ashraful et al., 2014). More than 90% of energy consumption from the transportation sector comes from fossil fuels and a small amount from natural gas and renewable energy sources (Atabani et al., 2012; Maity et al., 2014). The scarcity of the conventional oil and natural gas reserves will diminish after approximately 41.8 and 60.3 years, respectively (Ashraful et al., 2014). With this rapid increase in transportation fuel demand trends, environmental concerns and depletion of fossil fuels have become increasingly important to adopt policies to minimise the impact of global warming (Brennan and Owende, 2010) and also forces scientists and researchers to develop alternative fuels that can approximate the properties and performance of petroleum-based fuel (Tüccar and Aydın, 2013) to alternative biofuels. Therefore, alternative sources and renewable energy are becoming more feasible and urgently needed.

The Kyoto Protocol of 1997 pointed out a 5.2% reduction in GHG emissions worldwide from the values reported in the year 1990. Aircraft gas turbine exhaust is composed of carbon monoxide (CO), carbon dioxide (CO_2), water vapour (H_2O), unburned hydrocarbon (UHC), particulate matter (PM), nitrous oxide (NOX), sulphuric oxide (SOX) and excess of atmospheric oxygen and nitrogen. These emissions will definitely contribute to the GHG effects. Aware of these crises, tremendous efforts have been thoroughly planned such as Clean Sky JTI Projects by European countries, The Environmentally Responsible Aviation Project (ERA) by NASA and lots more. However, studies have shown that the development of more efficient technologies in aircraft engines reduces GHG emission up to 18% is still far below the goal of reducing 50% CO_2 emissions by 2050 (Payan et al., 2014). Due to these circumstances, aviation industries have shifted their strategy to use alternative fuels that are based from biofuels. Drop-in fuels and blended fuels in aircraft engines have significantly gained attention and interest from engineers and researchers globally. Drop-in fuels need less or no modification at all in the aircraft engine in service. It offers a future 'greener' aircraft and less dependency on crude oil.

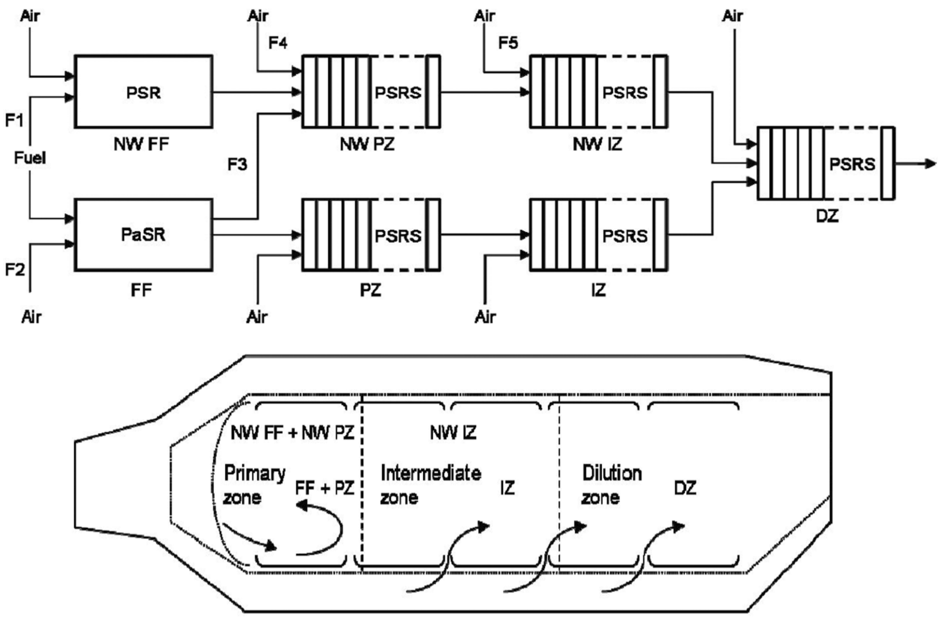
Three successful biofuel flights of commercial aircraft are Air New Zealand's Boeing 747-400, Continental Airlines Boeing 737-800 and Japan Airline Boeing 747-300. From these examples, it is found that there are no obvious signs of Synthetic Paraffinic Kerosene (SPK) blend impacting different engine operations using biofuel blended of up to 50% with conventional fuel (Rahmes et al., 2009). Following the successful flights of many commercial aircraft running with different biofuels, this reinforces that biofuel is a viable choice to sustain the environment as well as the energy. Several test flights have already been performed on blends of conventional jet fuel and bio-jet fuel from algae, Camelina, Jatropha and other plant-based feedstocks on commercial airlines and military aircraft (Fortier et al., 2014). However, sustainability is the main concern for biofuels in order to become a source of jet fuel. This refers to the ability of the biofuel to conserve ecological balance between productivity, biodiversity and natural sources. It is also worthy of mentioning that the usage of biofuels should not be compared with food production which has high oil yield in fast-growing crops.

The present study focuses on two aspects: aircraft engine performances and exhaust emissions analysis of these alternative fuels. First, the aircraft engine performance analysis studies the effect of different blended mixing ratio percentages of biofuels on aircraft engine performance especially on thrust, fuel flow and specific fuel consumption

(SFC) at different flight conditions. Two pure and blended biofuels (Jatropha Biofuel (BJ) and Camelina Biofuel (BC)) are evaluated at 20%, 40%, 60% and 80% of mixing ratio with kerosene. These fuels are selected following the success of the tested flight conducted on the commercial aircraft, drop-in fuel feasibility and comparable with open literature. A model three-shaft high-bypass-ratio engine, similar to RB211-524, was used throughout the analysis for validation and comparison with a RB211 variant in the work of Rahmes et al. (2009). Next, the emission analysis is presented to study the gas emission of NOX and CO with respect to these blended biofuels at different flight conditions.

Our in-house computer software was used for the computational analysis. PYTHIA was used for the engine performance analysis, whereas HEPHAESTUS was used for the emission analysis. PYTHIA utilised Newton-Raphson method convergence technique in a zero-dimensional steady-state model (Igie and Minervino, 2014) and it is integrated with our TURBOMATCH (Macmillan, 1974) code. PYTHIA is considered to be user-friendly (Mazlan et al., 2015) and has a novel interface for engine component selection that has the ability to design and calculate various gas turbine engines performances for both design and off-design points (PYTHIA interface shown in the appendix). HEPHAESTUS utilised the Zeldovich equations (for NOX) and modeled the emissions by implementing partially-stirred reactor (PSR) model in the first part of the combustor primary zone, and a series of perfectly stirred reactor (PSRS) models in later part of the combustor primary, intermediate, and dilution zones of conventional combustors. The configuration of the divided zones in the reactor is illustrated in Figure 1.

Figure 1 The configuration of divided zone in the reactor of the combustor



Source: Mazlan, 2012

PYTHIA and HEPHAESTUS capabilities have been tested and validated for many years (Li et al., 2011, 2012) ranging from the industrial gas turbine and aero gas turbine. The new version of PYTHIA has the capability to accommodate off-design conditions by changing the fuel type and varying the blended mixing ratio percentage. This is essential to evaluate fit-for-purpose fuel for real engines at various operating points. As the prediction of NOX and CO emission is complex and has become an active research area, this paper brings together the performance and emission analysis and makes a systematic study of its practicability in aircraft engine which has not been addressed in Azami and Savill (2016). Therefore, this paper serves as an extension of the previous works by accommodating both performance and emission analysis in our in-house software. It also offers wider prospects and opportunities for fuels selection versatility in both performance and emission researchers in gas turbine engines.

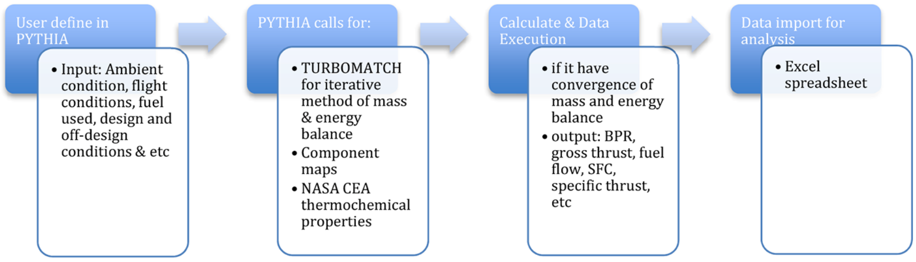
2 Methods

Both performance and emission studies are analysed separately using different software. TURBOMATCH became the computing core (the processor) integrated into PYTHIA (Macmillan, 1974). TURBOMATCH and PYTHIA will execute results accordingly while keeping the design conditions at fixed value. TURBOMATCH is called for the iterations in mass (Eq. 1) and energy (Eq. 2) balance relation. Equations (1) and (2) should be satisfied between successive components, via component matching, for example, between compressor and turbine and also a compatibility equation between turbine and nozzle. For a full range of gas turbine engines to be considered, every new shaft will involve two new unknowns that must be solved iteratively and two new equations must be introduced between the original components and the new one (Macmillan, 1974). New initial guess for pressure ratio, temperature (burner) and rotational speed must be made before the iteration process. The iteration process will need several initial guess values before it converges. Further details on the TURBOMATCH process are provided and explained in Macmillan (1974). The flowchart of the PYTHIA process is illustrated in Figure 2. It begins with the user defining inputs as previously mentioned in PYTHIA. Compressor and turbine maps were needed for mass balance iteration process. NASA Chemical Equilibrium Analysis (CEA) is applied for the evaluation of thermochemical fuel properties such as the correlation of enthalpy, flame temperature, specific heat and molecular formula to the function of temperature. These correlations are stored in the TURBOMATCH library data:

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

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

Figure 2 PYTHIA data process flowchart (see online version for colours)

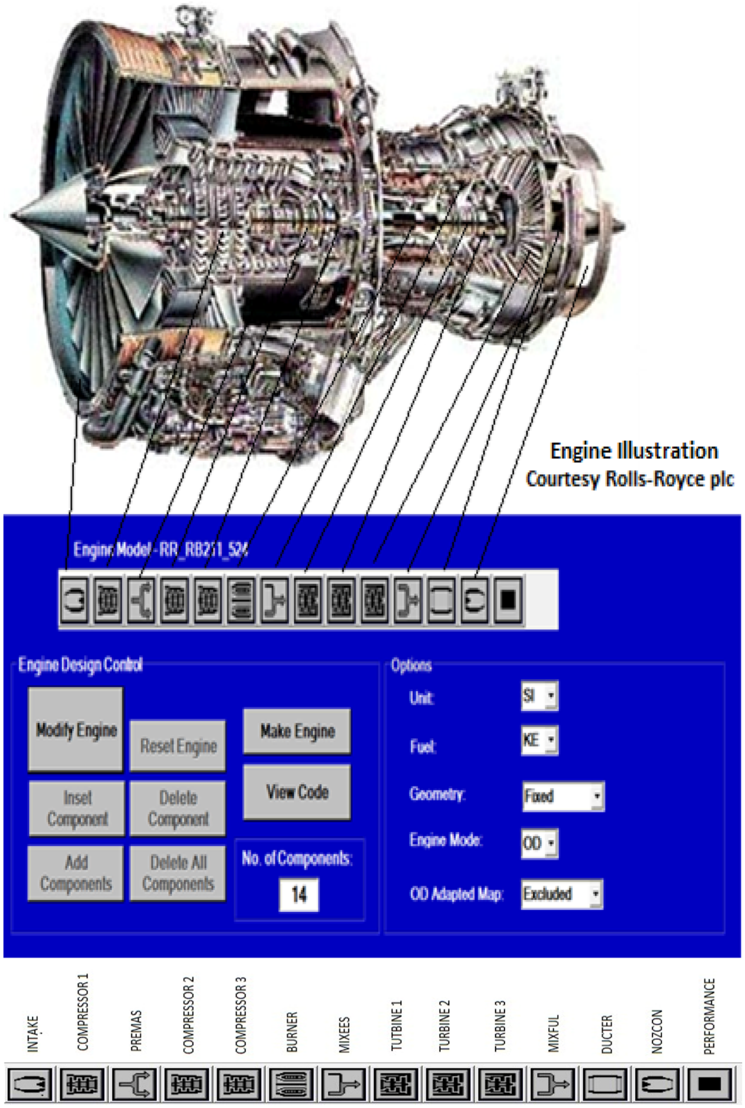


Source: Azami and Savill, 2016

Results obtained from PYTHIA in the combustor inlet conditions are used in HEPHAESTUS. The model engine configurations are specified in PYTHIA and illustrated in Figure 3. Results for the engine parameters and performance for the baseline fuel are tabulated in Table 1 and the fuel properties used in the analysis are included in the appendix. At design point, kerosene fuel was selected. Each component of the engine model is described in terms of 'bricks' which has its functionality. Initially, the ambient conditions were ascribed according to the intended flight conditions such as altitude, flight speed, mass flow, pressure recovery, pressure deviation and relative humidity in the intake 'brick'. The configuration of this engine was specified in PYTHIA using available library data and default settings. When the engine model is selected, 13 block data are arranged accordingly for: INTAKE, COMPRE1, PREMAS, COMPRE2, COMPRE3, BURNER, MIXEES, TURBIN1, TURBIN2, TURBIN3, MIXFUL, DUCTER and NOZCON as shown in Figure 3. Most bricks are defined as an individual component treating thermodynamic processes independently. However, they have to be linked to perform a complete engine simulation. In engine simulation, the properties and thermodynamic state of gasses at the entry of every Brick can be collected as a Station Vector (SV) to connect each brick. Each SV consists of following eight items (Li and Singh, 2005):

1 fuel-air ratio
2 mass flow
3 static pressure
4 total pressure
5 static temperature
6 total temperature
7 velocity
8 area.

Figure 3 Model engine configurations in PYTHIA (see online version for colours)



Source: Azami and Savill, 2016

Table 1 Engine parameters

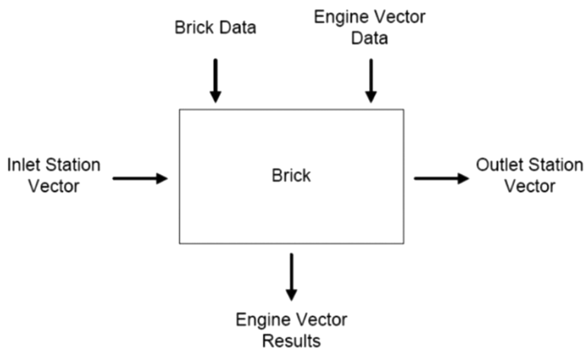
Intake	
Altitude (m)	10,588
Flight Mach number	0.84 (cruise) 0.34 (climb)
Mass flow intake (kg/s)	670
Combustors	
ETA	0.99

Table 1 Engine parameters

Pressure drop (atm)	1.29
Fuel flow (kg/s)	2.18
LHV (MJ/g)	43.12 (KE) 44.0 (BC) 44.3 (BJ)
FAR	0.02
Engine performances	
BPR	4.3
Gross thrust (kN)	293.38
Fuel flow (kg/s)	2.18
SFC (kg/Ns)	21.07

Figure 4 shows the schematic diagram of a brick inputs and outputs. For off-design conditions, three design parameters were adjusted accordingly in the burner ‘brick’, which are the fuel combination, second fuel type and fuel-mixing rate. Fuel combination parameter represents the condition of how the fuel is mixed. Apparently, there are three options for selection; keeping the original fuel, replacing the original fuel and mixing the fuel. The second fuel type is defined as the type of second fuel used. Fuel-mixing rate signifies the blending mixing ratio percentages from 0 to 1, where 1 is represents the pure second-type fuel.

Figure 4 Schematic diagram of brick data



Source: Li and Singh, 2005

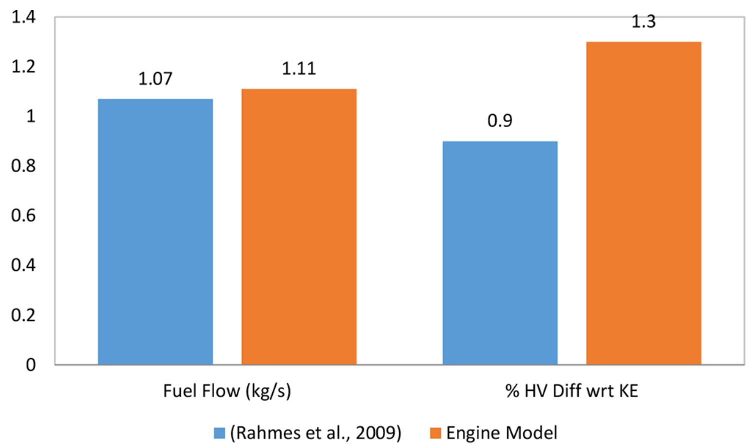
As previously mentioned, HEPHAESTUS requires several input data obtained from PYTHIA in combustor ‘brick’ data. Other parameters such as the combustor geometries, fuel total temperature, ambient conditions (altitude, temperature and relative humidity), air total pressure and temperature at the combustor inlet, fuel and total air mass flow rate are needed prior to the analysis. Combustor geometries are kept constant as per value used in Celis (2010) and Mazlan (2012). However, only the predictions of kerosene and BJ blended fuels for NOX and CO are considered in the emission analysis. Although there are quite a number of emission methods available to predict emission in the literature, HEPHAESTUS has shown its capability and versatility to predict emissions generated from biofuels with ease. Few assumptions need to be addressed prior to HEPHAESTUS analysis such as fuel evaporation, combustion unsteadiness and flow circulation in the combustor are not included. These assumptions are deliberately elaborated in Celis (2010) and Mazlan (2012).

3 Results and discussion

3.1 Engine performance validation

Prior to the analysis, the engine model developed in PYTHIA was validated by comparing with experimental work previously carried out by Rahmes et al. (2009), who conducted an off-wing engine ground test of an RB211-524 fuelled with 50% Jatropha/50% Jet-A on a Boeing 747-400 of the Air New Zealand airline. It appears that the fuel flow and percentage HV differences were comparable with the engine model, exhibiting only a slight difference as shown in Figure 5.

Figure 5 Performance validation of blended kerosene/BJ (see online version for colours)



3.2 Performance analysis

3.2.1 Take-off

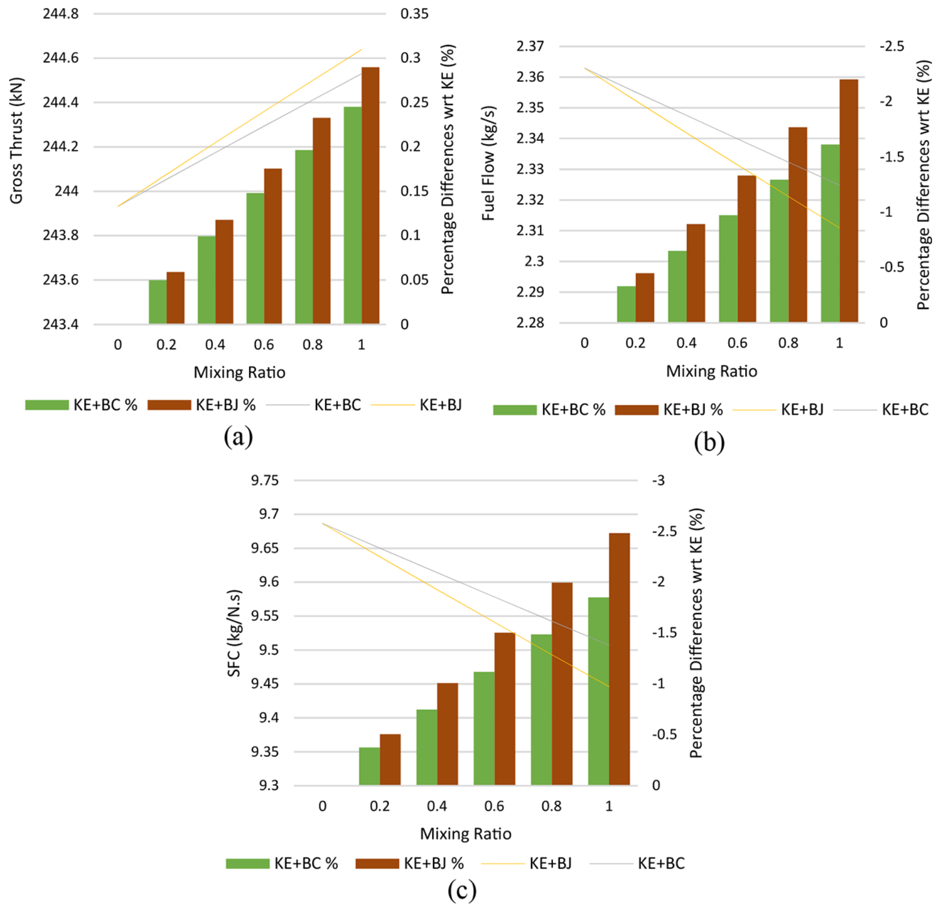
Initially, the propulsive performance at take-off condition is evaluated and analysed for different percentage blended mixing ratio. The ambient and initial flight conditions are adjusted accordingly in the first block diagram. Figure 6 demonstrates the

1 gross thrust

2 fuel flow

3 SFC

Figure 6 Variation of (a) gross thrust, (b) fuel flow and (c) SFC and its percentage difference with respect to pure kerosene at different mixing ratio (see online version for colours)



Variations and percentage differences as compared with kerosene at different mixing ratios. There was an increase in gross thrust for both fuel combinations as the mixing ratio moves towards pure biofuel (high mixing ratio). BJ pure biofuel showed 0.29% increase in gross thrust. The difference started to become more severe at higher mixing ratios. Fuel flow results revealed a reduction for both fuels as the mixing ratio was increased. The reduction was up to 2.2% and 1.6% of fuel flow for pure BJ and BC, respectively. Both fuels exhibited a reduction in SFC as the mixing ratio was increased. SFC was reduced up to 2.48% for BJ pure fuel, while for BC, it was reduced by 1.85%. These results thus suggest that better performance can be achieved using pure alternative fuels due to higher lower heating value (LHV). Detailed explanations are discussed at the end of this section.

3.2.2 Cruise

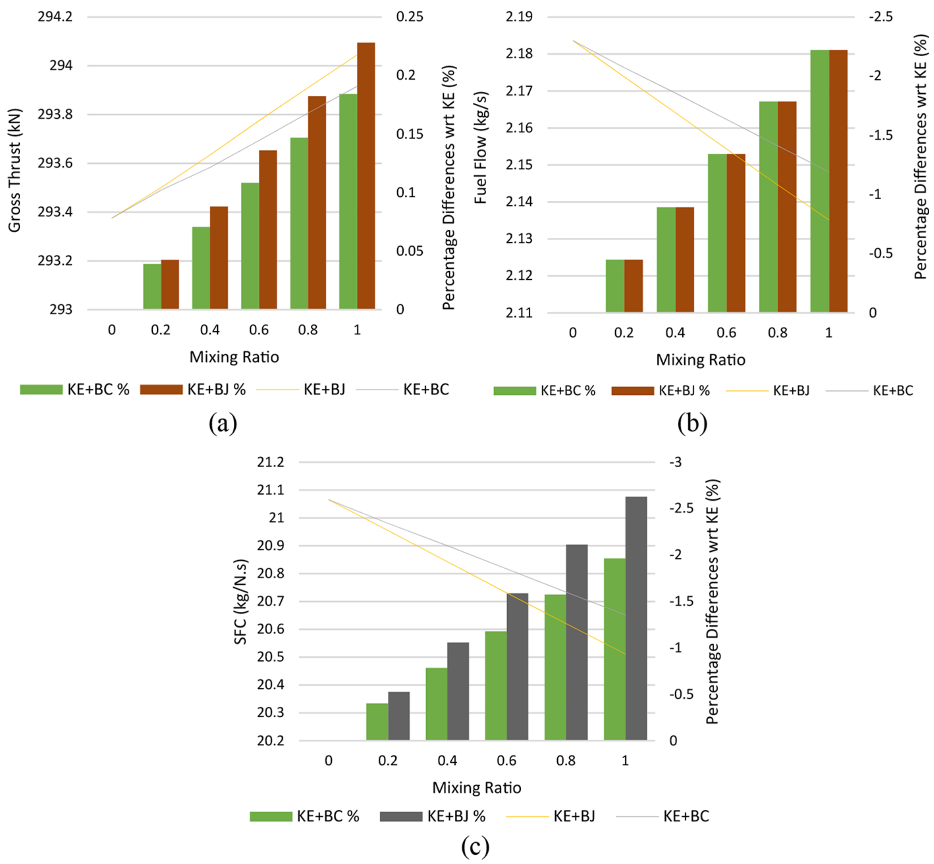
Cruise conditions as mentioned previously in Table 1 are used. Figure 7 illustrates the

1 gross thrust

2 fuel flow

3 SFC

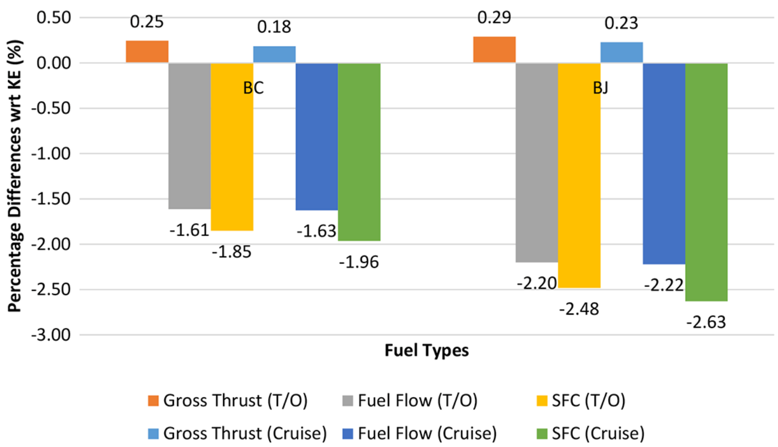
Figure 7 Variation of (a) gross thrust, (b) fuel flow and (c) SFC and its percentage difference with respect to pure kerosene at different mixing ratios (see online version for colours)



Variations and percentage differences as compared to kerosene. Similarly, there was an increase in gross thrust for both fuel combinations as the mixing ratio increases. It should be noted also that there is a slight reduction of gross thrust percentage differences in cruise condition compared to the take-off condition. Likewise, the fuel flow and SFC demonstrated a reduction for both fuel as the mixing ratio increased. There were not many differences between cruise and take-off conditions, for the fuel flow. However, SFC was reduced more in the cruise condition as compared to the take-off condition.

Results indicate a higher percentage of blended fuel demonstrate better propulsive performances. Comparisons of these pure alternative fuels can be summarised in Figure 8 for different flight conditions. Clearly, BJ performs much better than BC for gross thrust, more reduction in fuel flow and SFC for both different flight conditions. Furthermore, as the fuel flow and SFC give more improvement in cruise, however, there is a slight reduction in gross thrust at cruise condition as compared in take-off for both fuels.

Figure 8 Performance comparison of pure alternative fuel at different flight conditions (see online version for colours)



As alternative fuels are introduced into the combustor, few assumptions should be addressed. Combustion efficiency is assumed to remain fixed for all fuels which turned out to be varied in terms of fuel atomisation and spray characteristics due to the differences in thermochemical properties. The properties of alternative fuels used are taken directly from the published literature without taking consideration of ASTM approval and the fuel process methodology. Focusing only on the combustor with different of blended fuels, several results can be drawn due to the effect of the changed thermochemical properties. It is observed that the total pressure, the mass flow and the pressure drop increased slightly at higher percentage blended mixing ratio. As the total pressure and mass flow rise, the exit velocity is increased and this has resulted in an increase in gross thrust. However, the pressure drop in the combustor is increased as well. Furthermore, the fuel-to-air ratio (FAR) is reduced, indicating that more air is introduced to complete the burning. These explained more fuel flow reduction at higher mixing ratio blend. Although large LHV fuel gives a better propulsive performance, it is more likely to require more air for combustion. Another crucial parameter is the turbine inlet temperature (TIT) as it determines the propulsive performances but there are limitations to set the value due to the turbine materials integrity as well as observing NOX exhaust emission due to high temperature. TIT was set to 1,580 K for all cases. It is observed that high LHV fuel able to sustain the temperature longer which essentially important to expand and convert high energy to useful work and kinetic energy.

3.3 Emission analysis

This section studies the emission of these blended biofuels based on the performance parameters obtained in the previous analysis using PYTHIA. In HEPHAESTUS, kerosene fuel is selected as the baseline fuel. An LTO cycle includes three phases of an aircraft mission: cruise, climb and take-off. In the later section, the emission is analysed at different combustor inlet conditions. It is, however, only 50% blended KE+BJ (known as BJ50) and pure BJ fuel will be discussed due to limited capability in HEPHAESTUS. Prior to the analysis, it was observed to follow the trends provided in ICAO databank as shown in Figure 9. Among the three flight conditions, cruise phase has the largest differences as the ICOA databank covers only up to 3,000 ft altitude (Chandrasekaran and Guha, 2012). A list of emissions emitted and its differences with respect to kerosene fuel is tabulated in Table 2 for comparison. It is observed that blended and pure biofuel contributes to the reduction in EINOX at every flight condition for about 4–12% with respect to kerosene fuel. Pure Jatropha biofuel demonstrates the most NOx reduction. Nevertheless, EICO values for these blended biofuels predicted by HEPHAESTUS depicted a slight increase for about 2% (except for BJ fuel). Yet, pure Jatropha biofuel has a much lower increase in EICO as compared to BJ50.

Figure 9 Emission comparison of baseline kerosene fuel at different flight conditions with ICAO databank (see online version for colours)

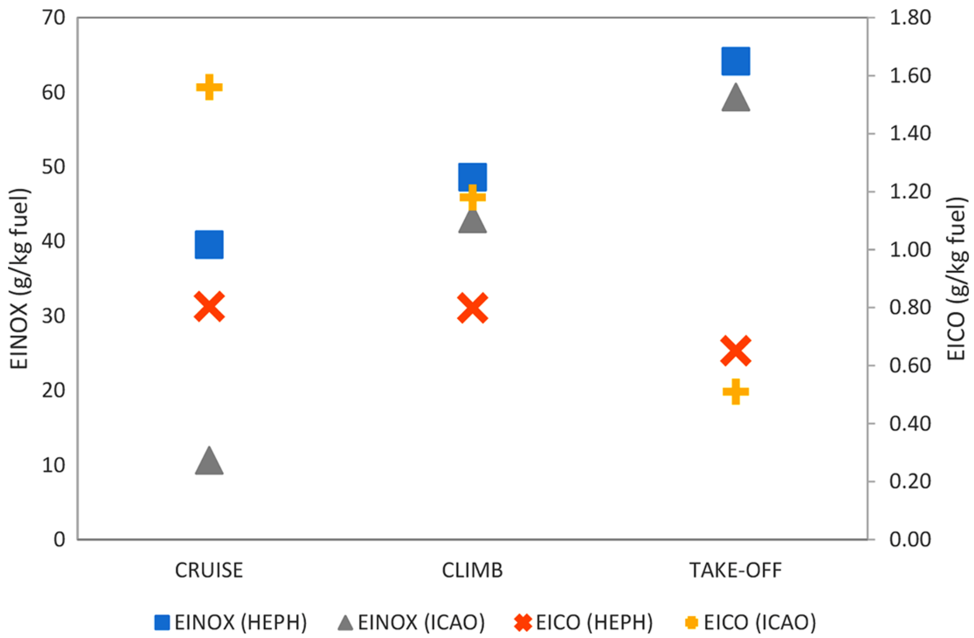


Table 2 Emission comparison of alternative blended biofuels at different flight conditions

	TA (K)	*PA (atm)*	*WA (kg/s)*	*WF (kg/s)*	*TF (K)*	*EINOX (g/kg fuel)*	*EICO (g/kg fuel)*	*Δ% EINOX wrt KE*	*Δ% EICO wrt KE*
Cruise									
KE	840.39	19.56	72.26	1.54	413.74	39.56	0.80		
BJ50	840.88	19.58	72.35	1.53	413.82	37.22	0.81	−5.91	0.75
BJ	841.37	19.60	72.44	1.51	413.90	35.70	0.81	−9.77	0.55
Climb									
KE	847.24	21.17	72.02	1.53	413.93	48.60	0.80		
BJ50	845.98	20.95	71.33	1.50	414.00	44.66	0.81	−8.11	1.97
BJ	846.51	20.98	71.43	1.48	414.08	42.86	0.81	−11.82	1.76
Take-off									
KE	852.08	30.69	113.62	2.43	414.28	64.15	0.65		
BJ50	853.59	30.95	114.6	2.41	414.35	61.30	0.65	−4.44	0.18
BJ	854.19	31.01	114.89	2.39	414.43	58.94	0.65	−8.13	−0.03

3.3.1 Variation of combustor inlet conditions

Variations of different inlet conditions such as combustor inlet pressure, temperature, mass flow rate and fuel flow rate are presented in this section. The left side of Figure 10a–c illustrates the EINOX and EICO variations under the influence of combustor inlet pressure. Results display an increase in EINOX as the combustor inlet pressure increases at every flight condition, but pure Jatropha biofuel has much lower EINOX emission. Similarly, EICO variations increased as inlet pressure increases except for take-off flight phase condition. At this condition, EICO has the highest value at about 30 atm before it starts to decline. As expected, BJ50 fuel has much higher EICO than other fuels. Moreover, the right side of Figure 10d–f depicted the influence of combustor inlet temperature to EINOX and EICO variations. Apparently, the opposite effects occurred in EINOX and EICO variants; EINOX increases and EICO decreases as the combustor inlet temperature increases. EINOX emission increases as the combustor inlet mass flow increase for every flight condition as illustrated in Figure 11a–c. Conversely, the effect fuel flow reduces the EINOX as shown in Figure 11d–f. Meanwhile, EICO has an optimum inlet mass flow rate and fuel flow rate for different flight phases before it starts to decline. For cruise and climbing phases, the highest EICO occurred at 1.5 kg/s of fuel flow, while during take-off, it is about 2.5 kg/s. From the preceding results in Figures 10 and 11, it can be summarised as follows:

1 EINOX can be reduced at lower combustor inlet pressure, inlet temperature and inlet mass flow but higher fuel flow rate.

2 EICO can be minimised at lower combustor inlet pressure (only at cruise and climbing phases) and higher inlet temperature, However, combustor inlet mass flow and the fuel flow rate have its optimum operating initial conditions and are dependent on the flight conditions.

3 BJ50 and BJ pure fuel can reduce EINOX for every flight condition. Nevertheless, the trends in EICO emissions depend on the flight conditions as well as variations of combustor inlet conditions.

Figure 10 Emission comparison of combustor inlet pressure variations, (a)–(c) and inlet temperature variations, (d)–(f), at different flight conditions (see online version for colours)

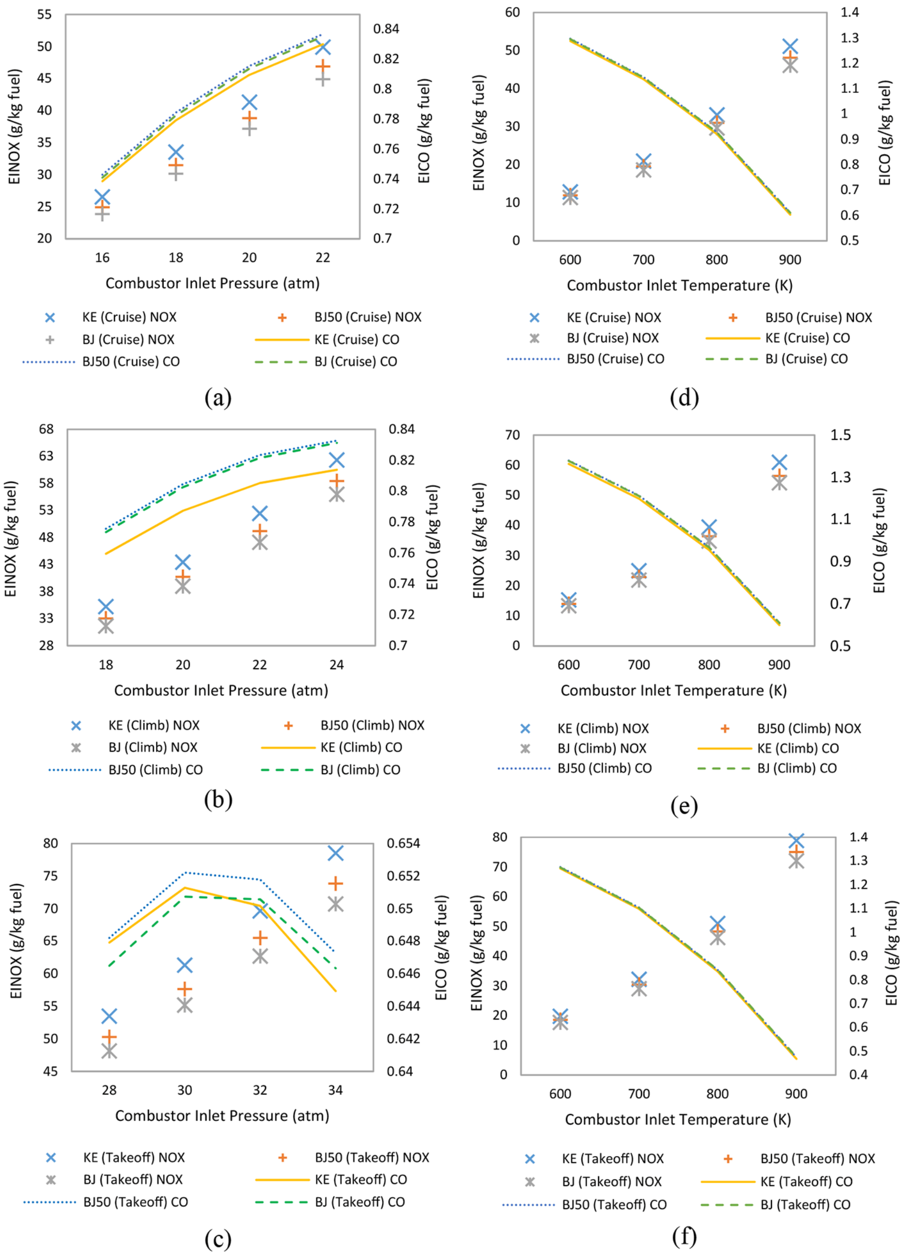
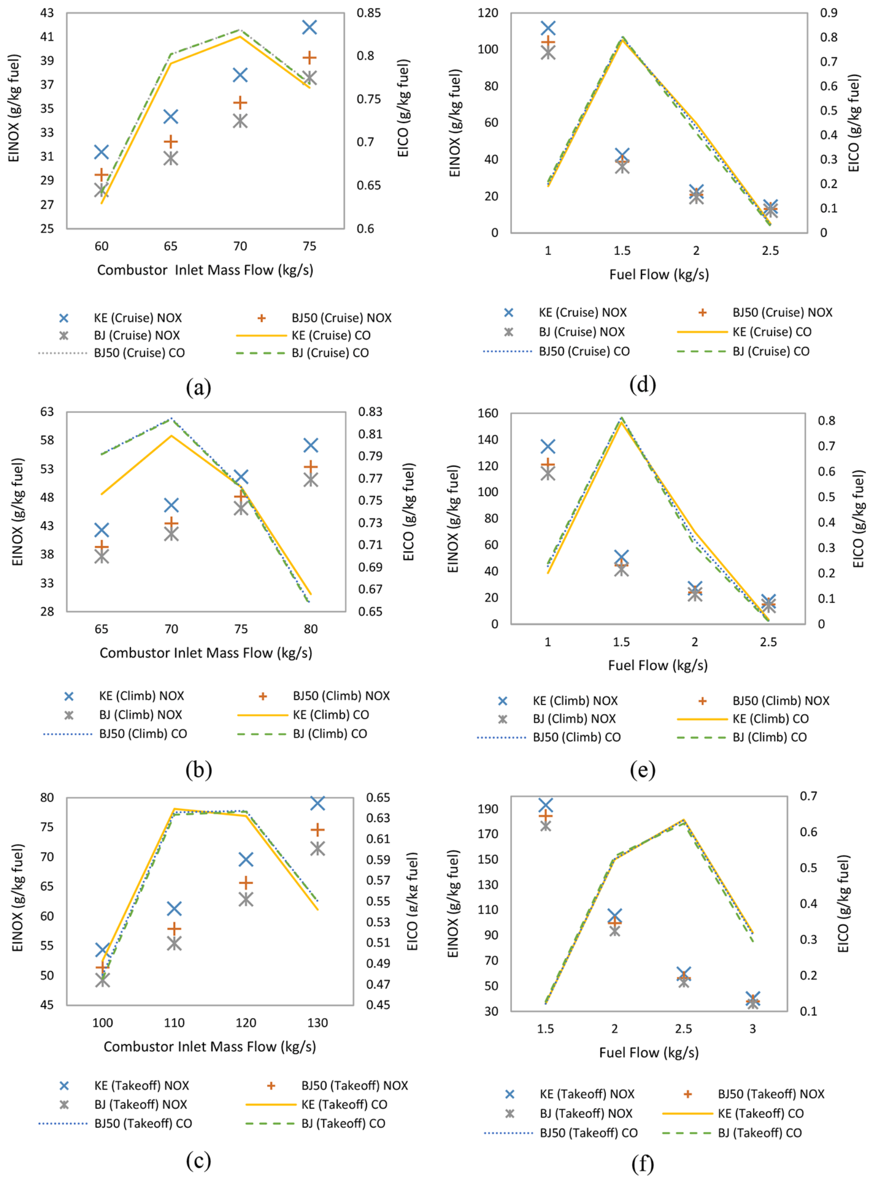


Figure 11 Emission comparison of combustor inlet mass flow variations (a)–(c), and inlet fuel flow variations, (d)–(f), at different flight conditions (see online version for colours)



4 Conclusion

Many important findings are brought together in this paper in terms of aircraft engine performance and emissions for alternative fuels using, respectively, in-house software codes: PYTHIA and HEPHAESTUS. It is observed that the LHV of the fuel has a significant influence on the engine performance metrics such as thrust, fuel flow and SFC at every flight condition and at different blended mixing ratio percentages. Results indicate a higher percentage of blended fuel demonstrated better propulsive performances. Clearly, Jatropha Biofuel performs much better than Camelina Biofuel for gross thrust, more reduction in fuel flow and SFC.

Emission analysis has been included in this paper and at the same time, its prediction of EINOX and EICO compares well with that of the ICAO databank. We have also shown that the combustor inlet conditions take an important role to determine EINOX and EICO emissions. For such variations, alternative fuels can reduce EINOX as compared to kerosene fuel for every flight condition. However, the same is not necessarily true for EICO emissions which depend on combustor inlet conditions and flight phases.

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Nomenclature

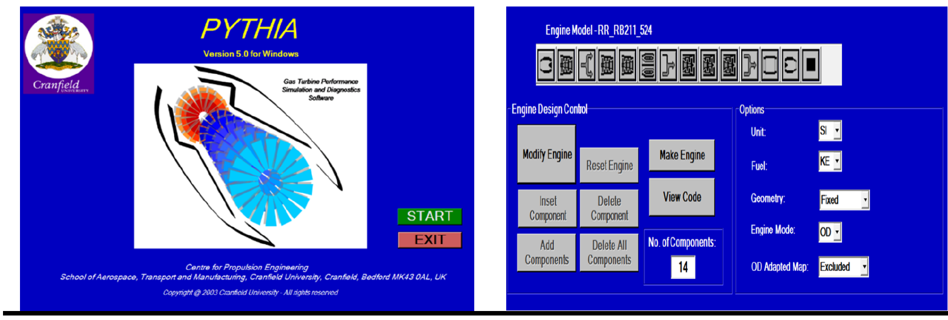
BC	Camelina biofuel
BJ	Jatropha biofuel
BPR	bypass ratio
CFPP	cold filter plugging point
ETA	efficiency
FAR	fuel-to-air ratio
KE	kerosene
LHV	lower heating value
P	pressure
P_n	pressure at n-stage
PR	pressure ratio
SFC	specific fuel consumption
T	temperature
TIT	turbine inlet temperature

T_n	temperature at n-stage
v_a	flight approaching speed
WA	mass flow
W_n	mass flow at n-stage
Z	surge margin parameter

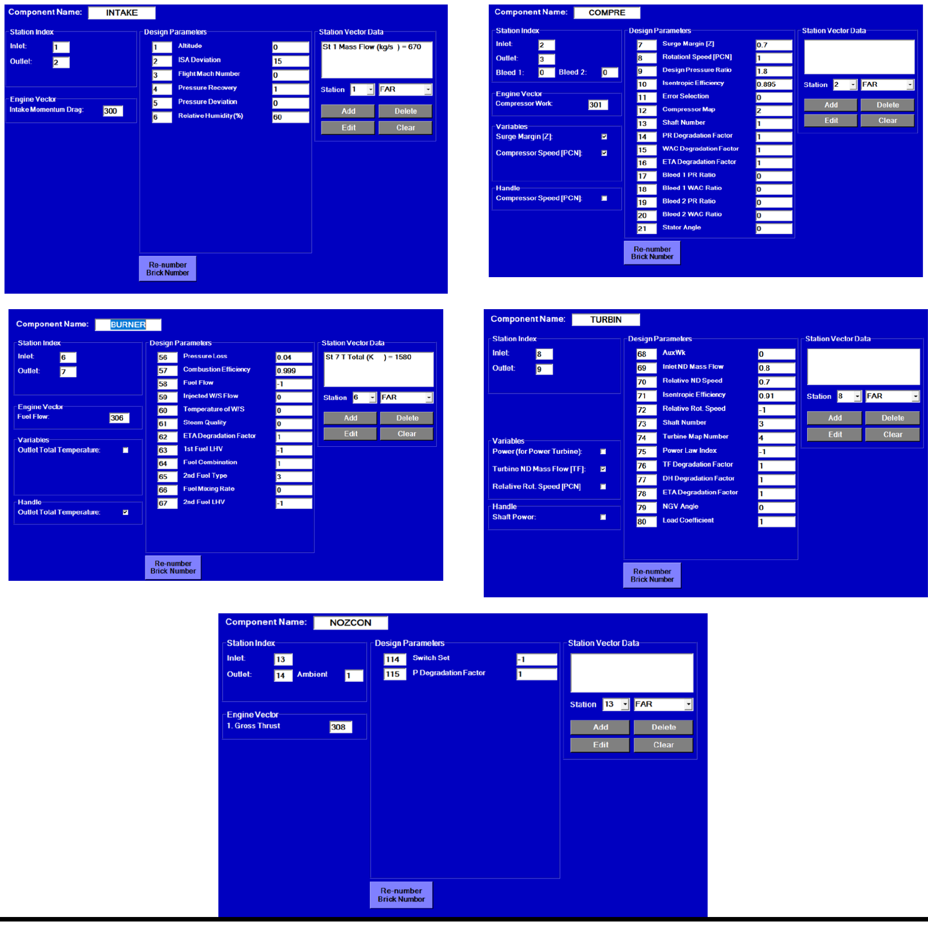
Appendix

	Jatropha	***Camelina***
Density (kg/m^3)	864–880	–
Cetane number	46–55	50.4
Viscosity (mm^2/s at 40°C)	3.7–5.8	3.80
Pour point (°C)	5	−7
Flash point (°C)	163–238	136
Heating value (MJ/kg)	44.4	44
CFPP (°C)	−1.2	−3
Acid value (mg/KOH)	0.34	
Cloud point (°C)	5	3
Iodine value (I_2/100 g)	109.5	152.8
Sulphur content (ppm)	12.9	–
Specific gravity (g/ml)	0.876	0.882
Molecular formula	$C_{12}H_{26}$	$C_{12}H_{25.4}$

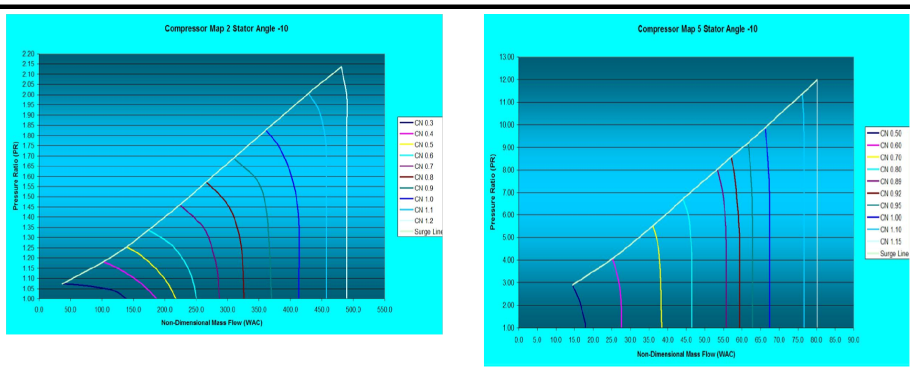
PYTHIA user interface (see online version for colours)



PYTHIA user interface (see online version for colours) (continued)



Compressor map used (see online version for colours)



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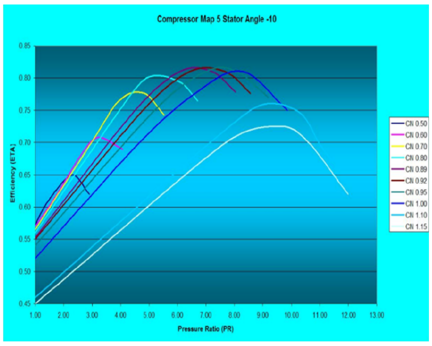

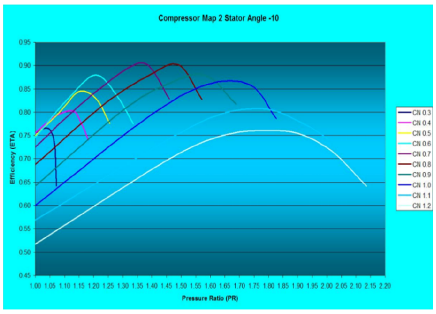

Turbine map used (see online version for colours)