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Abstract

Jatropha-derived fuels has potential as alternative aviation fuels, their effects on turbofan performance depend on fuel composition and operating conditions. This study numerically investigates the performance of Jatropha-derived fuel blends in an RB211-524-class high-bypass turbofan engine. A multicomponent surrogate was developed for the Jatropha-derived fuel and combined with a Jet A-1 surrogate at 25%, 50%, and 75% Jatropha fractions by mass, together with neat Jatropha-derived fuel. A combination of NASA Chemical Equilibrium with Applications (CEA), GasTurb Detail 6, and Gas Turb 15 was used to evaluate thrust, thrust-specific fuel consumption (TSFC), core thermal efficiency, fuel flow, exhaust gas temperature (EGT), and NOx

severity parameter at the design point and across off-design altitudes from sea level to 11,000 m. At the design point, increasing the Jatropha-derived fuel fraction produced a maximum thrust increase of 0.306%, TSFC reduction of 2.298%, core thermal-efficiency increase of 0.249 percentage points, and fuel-flow reduction of 1.999%, while EGT increased by 0.181%. The NO_x severity parameter varied by less than 0.001%. Off-design results shows altitude has a substantially greater influence on engine operating parameters than fuel composition. The trends suggest modest performance changes with Jatropha-derived fuel substitution, while further experimental validation and fuel compatibility assessment are required.

Keywords: Jet A-1; RB211-524; Turbofan engine; GasTurb 15; Design point performance; Off-design altitude sweep; Thrust; Thrust-specific fuel consumption (TSFC); Core thermal efficiency; Exhaust gas temperature (EGT); NO_x severity parameter; Fuel Flow.

1. Introduction

Jatropha, camelina, and algae, especially ones sourced from non-food Biomass and algae improves the sustainability by reducing greenhouse gas (GHG) emissions, as this source of biofuels do not compete with food or freshwater resources, and they do not cause deforestation, while also providing socioeconomic benefit to local communities [1]. Studies into biofuel have gained significance due to demand for sustainable energy sources in the aviation industry which has prompted researchers to explore alternatives fuels and propulsion system [2], especially with NASA's interest in making or reducing aircraft fuel consumption by an impressive 70% by 2025 [3],[4], as a result of this changes and interest, biofuel became a viable alternative to conventional fossil fuels. Biofuel derived from renewable biomass sources, such as Bio-Synthetic Paraffin Kerosene (Bio-SPK), offer significant reduction in carbon emissions while maintaining compatibility with existing fuel infrastructure[5]. Research into biofueled engines also underscores the importance of optimizing biofuel properties for engine compatibility and combustion efficiency must be addressed to maximize the potential of these engines. Studies have shown that tailoring biofuels to match engine requirements can significantly improve their performance, making them practical alternative to conventional aviation fuels [6]. Similarly, usage of bio renewable alternative fuel resources from biofuel (ethanol or biodiesel) has produced promising solutions to reduce some toxic emissions of Sulphur, nitrogen oxide (NO), NO₂ and CO [7]. Although previous studies have demonstrated the feasibility of Jatropha-based aviation fuels through experimental investigations and numerical simulations, most have focused on a limited range of operating conditions or individual engine performance parameters. Consequently, a comprehensive assessment of Jatropha fuel blends over the complete operating envelope of a modern turbofan engine remains limited. This study addresses this gap by developing an integrated NASA CEA - GasTurb simulation framework to evaluate the performance of Jet A-1 /Jatropha blends in a Rolls-Royce RB211-524 turbofan engine. Both design-point and off-design operating conditions are investigated to quantify variations in thrust, thrust-specific fuel consumption, fuel flow, thermal efficiency, exhaust gas temperature, and NO_x emissions. By combining fuel-property generation with full-cycle engine simulation across the flight envelope, this work provides a more

comprehensive understanding of the operational performance of Jatropha biofuel blends than has been reported in previous studies.

2. Materials and Methods

Performance is modelled at various altitudes using Jet A-1 and Jatropha blends at both design and off design. It starts with defining engine configuration, assigning fuel properties, configuring the combustion model, performing simulations, analyzing results and drawing conclusions at both design and off design point. There was no engine or flight test for this engine in this study the simulation output are not validated with experiments, fuel physiochemical properties and blend related trends reported by Rhames et al, 2009[5], for Jatropha-derived Bio-SPK, flight and ground engine tests were used as an independent reference to check that the fuel properties and qualitative performance trend produced by simulation are physically reasonable and consistent with published results; this the comparism is a literature benchmark of trends and fuel property, not a quantitative validation of the present model's absolute engine prediction against dedicated experimental data,. The software used for this analysis is the GasTurb detail 6 combined with the NASA CEA (Chemical Equilibrium with Application) Code and the GasTurb 15. The primary software used for this research is the GasTurb 15, which serves as the main tool for the engine simulation, this software is designed for gas turbine cycle calculations, offering modelling capabilities that are crucial for analysing the performance of turbofan engine, turbo prop, turbojet and turboshaft engine. GasTurb 15 has the ability to simulate off-design performance, this was useful for understanding the behavior of the propulsion system under varying flight condition (takeoff, cruise, descent). The simulation was done in phases, the first being the Design Point, It was ensured that same value of basic data as shown in Table 1 was used in each case for comparison, it was modeled to represent the Rolls-Royce RB211-524 on GasTurb 15.

Table 1: Engine Parameters and corresponding value for the Rolls-Royce RB211-524 on GasTurb 15 [2]

S/N	Engine Parameter	Unit	Value
1.	Intake Pressure Ratio		0.99
2.	No (0) or Average (1) Core dP/P		1
3.	Inner Fan Pressure Ratio		4
4.	Outer Fan Pressure Ratio		3.5
5.	Core Inlet Duct Press. Ratio		1
6.	IP Compressor Pressure Ratio		2
7.	Compr. Interduct Press. Ratio		0.98
8.	HP Compressor Pressure Ratio		7
9.	Bypass Duct Pressure Ratio		0.975

10.	Inlet Corr. Flow W2Rstd	kg/s	670
11.	Design Bypass Ratio		1.5
12.	Burner Exit Temperature	K	1800
13.	Burner Design Efficiency		0.9995
14.	Burner Partload Constant		1.6
15.	Fuel Heating Value	MJ/kg	43.124
16.	Rel. Handling Bleed to Bypass		0
17.	Rel. HP Leakage to Bypass		0
18.	Overboard Bleed	kg/s	0
19.	Rel. Overboard Bleed W_Bld/W25		0
20.	Rel. Enthalpy of Overb. Bleed		1
21.	Recirculating Bleed W_reci/W25		0
22.	Rel. Enthalpy of Recirc Bleed		1
23.	Rel. HP Leakage to LPT exit		0
24.	Number of HP Turbine Stages		1
25.	HPT NGV 1 Cooling Air / W25		0.05
26.	HPT Rotor 1 Cooling Air / W25		0.06
27.	HPT NGV 2 Cooling Air / W25		0
28.	HPT Rotor 2 Cooling Air / W25		0
29.	HPT Cooling Air Pumping Dia	M	0
30.	Number of IP Turbine Stages		1
31.	IPT NGV 1 Cooling Air / W25		0.02
32.	IPT Rotor 1 Cooling Air / W25		0.005
33.	IPT NGV 2 Cooling Air / W25		0
34.	IPT Rotor 2 Cooling Air / W25		0
35.	Rel. Enth. of IPT Cooling Air		0.6
36.	Number of LP Turbine Stages		4

37.	LPT Rotor Cool Air W_Cl_LPT/W25	0.01
38.	Rel. Enth. of LPT Cooling Air	0.7
39.	Rel. Fan Overb.Bleed W_Bld/W13	0
40.	Core-Byp Heat Transf Effectiven	0
41.	Coolg Air Cooling Effectiveness	0
42.	Bleed Air Cooling Effectiveness	0
43.	Power Offtake kW	50
44.	HP Spool Mechanical Efficiency	0.98
45.	IP Spool Mechanical Efficiency	1
46.	LP Spool Mechanical Efficiency	1
47.	Burner Pressure Ratio	0.95
48.	IPT Interd. Ref. Press. R atio	0.992
49.	LPT Interd. Ref. Press. Ratio	1
50.	Turbine Exit Duct Press Ratio	0.99
51.	El. Fan Design Bypass Ratio	1

The fuel file to be used by the GasTurb 15 software was first generated on the GasTurb Detail 6 software. The generation of the fuel data file involves using the NASA CEA (Chemical Equilibrium with Applications) program and GasTurb detail 6, following strict procedure that aligns with the GasTurb Detail 6 User Guide [8], which is use to blend the Jatropha biofuel with Jet A-1 and calculate the chemical equilibrium compositions and properties of complex mixture to determine the thermochemical fuel properties such as the correlation of enthalpy, flame temperature, specific heat and molecular formula to the function of temperature of the biofuel to be used for the simulation. The biofuel namely JeJa 75/25, JeJa 50/50, JeJa 25/75 while CEA, written in FORTRAN, is widely used in aerodynamics and thermodynamics[9],[10], GasTurb Details 6 simplifies the creation of input data sets for temperature rise due to combustion and gas properties of air and combustion gases, input file from NASA CEA were run through the FCEA2.exe program, which output files that GasTurb Detail 6 combines into a single file for the new fuel, also ensuring that the name was added to the Fuel.gtb file. The steps include naming the fuel, entering fuel composition, specifying paths to the necessary programs, creating and running the required input files, and finally, generating the GasTurb files.

Table 2: Physiochemical Properties of Jatropha biofuel and Jet A-1 fuel[5]

Property	Jatropha Biofuel	Jet A-1 Fuel
Density at 15 ⁰ C, (g/cm ³)	0.749	0.775 –0.840
Viscosity (mm ² /s at -20 ⁰ C)	3.663	8
Flash Point (°C)	163-238	38
Cloud Point (°C)	5	-40
Pour Point (°C)	5	-47
Saponification Value	186 – 195S	N/A
Iodine Value (g I ₂ /100g)	109.5	N/A
Acid Value (mg KOH/g)	0.34	0.10
Heating Value (MJ/kg)	44.3	42.8
Oxidative Stability (h)	5.0	N/A
Free Fatty Acid Content	< 0.5%	N/A
REFERENCES	[2], [5]	[5]

2.1 NO_x Emission (Severity Parameter)

Severity parameter measures the intensity and potential consequences of nitrogen oxide emissions specifically from aircraft combustion processes. “Severity parameter for NO_x emission” to assess the relative amount of nitrogen oxides (NO_x) an engine produces[11]. This parameter considers both the engines maximum NO_x emissions and its thrust capability, allowing for comparison between engines of different sizes. Lower severity parameter indicates a cleaner engine design.

The expression for determining severity parameter is given as thus[12] :

$$S_{NO_x} = \left(\frac{P_3}{2965kPa} \right)^{0.4} \cdot e^{\left(\frac{T_3 - 826k}{194k} + \frac{6.29 - 100.war}{53.2} \right)} \quad (1)$$

Where:

- P_3 = Pressure at the last compressor exit, cold side heat exchanger inlet of the gas turbine engine.

- T_3 = Temperature at the last compressor exit, cold side heat exchanger inlet of the gas turbine engine
- War = water-air-ratio

The NO_x emission index for aircraft engines is a crucial metric that quantifies the amount of nitrogen oxides produced per unit of fuel burned. It is typically expressed in grams of NO_x per kilogram of fuel (g/kg)[13]. This index provides insight into the environmental efficiency of an aircraft engine, indicating how much NO_x is generated relative to fuel consumption[14]. High NO_x emission levels are associated with greater environmental harm, including contributions to ground-level ozone formation and acid rain, which have significant health and ecological impacts while lower NO_x EI indicates a cleaner burning engine, producing less air pollution[15]. This index is crucial for both environmental regulations set by bodies like the International Civil Aviation Organization (ICAO) and for designing fuel-efficient engines, as complete combustion reduces both NO_x and fuel consumption[16]. The emission Index (EI) varies linearly with the NO_x severity parameter for conventional combustors thus:

$$EI \approx 32 * S_{NO_x} \quad (2)$$

While for dual annular combustors the NO_x emission is approximately

$$EI \approx 23 * S_{NO_x} \quad (3)$$

Where:

S_{NO_x} = severity parameter

This research work adopted conventional combustors.

2.2 Thrust

Thrust is a fundamental parameter for comparing various aircraft engines, as it directly measures the engine's ability to propel the aircraft forward[17]. By analyzing thrust, engineers can determine how well different designs meet the operational demands of various aircraft, such as takeoff, climb, and cruise performance. Additionally, comparing thrust across engines provides insights into the balance between fuel efficiency, emission reductions, and power output, guiding advancements in sustainable aviation technology and informing design choices to optimize performance while minimizing environmental impact[18].

The expression for thrust used in GasTurb 15 for static condition where $V_o = 0$ m/s is as thus[12]:

$$F = A_8 \cdot P_{amb} \cdot \frac{2\gamma}{\gamma-1} \left[\left(\frac{P_8}{P_{amb}} \right)^{\frac{\lambda-1}{\gamma}} - 1 \right] \quad (4)$$

Where:

- A_8 = Area of the nozzle throat.
- P_{amb} = ambient pressure.
- γ = adiabatic index (heat capacity ratio)
- P_8 = pressure at nozzle exit.
- λ = air-fuel ratio ($0 < \lambda \leq 1$)

2.3 Thrust Specific Fuel Consumption

Thrust Specific Fuel Consumption (TSFC) for propulsion system is a key metric used to evaluate the efficiency of engines that combine conventional jet fuel, Biofuel and electric power[19]. TSFC measures the amount of fuel required to produce a unit of thrust over a specific period. In systems, the inclusion of electric propulsion can significantly reduce fuel consumption and emissions, as electric engines are more efficient and produce no direct emissions. This metric is crucial for the development and performance assessment of next-generation aircraft that prioritize sustainability and efficiency.

$$TSFC = \frac{f}{F_T/\dot{m}_0} = \frac{\dot{m}_f}{F_T} \quad (5)$$

where:

- f = fuel air ratio
- F_T = The thrust
- $\dot{m}_f$ = fuel flow rate[12]

The investigation into thrust-specific fuel consumption (TSFC) is crucial for assessing the range of Aircraft. According to the Brequet range equation Equation 6, TSFC exhibits an inverse relationship with aircraft range. Specifically, increased TSFC values lead to reduced range, whereas decreased TSFC values facilitate an extended range.

$$R = \frac{V_\infty}{TSFC} \frac{L}{D} \ln \frac{W_0}{W_1} \quad (6)$$

Where:

- R is the Range.
- V_∞ True airspeed of the aircraft.
- TSFC is the thrust specific fuel consumption (TFSC) for the turbine engine
- $\frac{L}{D}$ is the Lift-to-Drag ratio.
- W_0 is the gross weight (with full fuel tanks) of the aircraft.
- W_1 is the weight with the aircraft fuel tanks empty.

For comparison, it is ensured that the all parameters in Equation 6 aside the TSFC is kept constant and is uniform for all the engines.

When a jet engine operates outside of its normal design parameters that is, when temperature, altitude, and Mach number differ from the expected values this is known as the engine's off-design point. Analyzing off-design situations is essential since they can affect emissions, engine efficiency, and performance [6]. Variations in Mach number, altitude, compressor pressure ratio, turbine inlet temperature, and afterburner exit temperature are examples of variables that can affect off-design situations, which can affect thrust output and engine efficiency [7] and this shows the actual working condition of the RB211-524. Table 3 below shows the ambient conditions of the air at the off-design point.

Table 3: Ambient Conditions use for the off-design point calculation.

Property	Unit	Value	Comment
Altitude	m	0 to 11000	
Delta T ISA	K	0	
Relative Humidity [%]		60	
Mach Number		0.7	Mach Number at cruise speed

2.3 Selection of the Generated Fuel File

Fuel Surrogate Formulation

Jatropha-derived fuel is a multicomponent mixture rather than a single chemical species, a surrogate-fuel representation was adopted for the combustion calculations. The surrogate was implemented using NASA's Chemical Equilibrium with Applications (CEA) software and GasTurb Detail 6. The corresponding molecular weights, mole fractions, and mass fractions used in the CEA fuel definition are given in Table 4, Table 5, Table 6, Table 7, Table 8. The surrogate composition was used consistently for all Jatropha and JetA1 fuel cases, while the Jet A-1 and Jatropha components were subsequently combined according to the specified blend ratios. CEA and GasTurb Detail 6 was then used to determine the combustion-equilibrium properties required for the subsequent GasTurb engine simulations, it is important to note that the Assigned Enthalpy for each compound was gotten from National Institute of Standards and Technology[20]. Jatropha surrogate species listed below in table 4 are saturated and unsaturated free fatty acids (e.g., myristic, palmitic, stearic, oleic, linoleic, and arachidic acid), which are representative of the underivatized, oxygen-containing composition of crude Jatropha curcas oil rather than of a fully hydroprocessed, deoxygenated Bio-SPK paraffin fraction of the type produced by the UOP Renewable Jet Process and reported by Rahmes et al (2009).

Table 4: Jatropha Surrogate Fuel Compositions[21],[22],[23].

IN LIB	Formula	Ass Enth	Molec.W	Mole Frac	Mass Frac
no	C14H28O2	-834.1	228.374	0.0170	0.0140171
no	C16H32O2	-848.4	256.428	0.1550	0.143502
no	C18H36O2	-891	284.481	0.0705	0.0724111
no	C18H34O2	-764	282.465	0.3872	0.394878
no	C18H32O2	-634.7	280.45	0.3682	0.372822
no	C20H40O2	-1012.6	312.535	0.0021	0.0023696
				Sum	1 / 1

Table 5: JETA1 Surrogate Fuel Compositions[24], [25].

IN LIB	Formula	Ass Enth	Molec.W	Mole Frac	Mass Frac
no	C9H12	-61.9	120.194	0.1171	0.0657916
no	C12H26	-364.3	170.337	0.13045	0.103889
no	C11H24	-327.2	156.311	0.09665	0.0706191
no	C11H22	-233.7	154.295	0.1558	0.11237
no	C14H28O2	-834.1	228.374	0.0085	0.0090735
no	C16H32O2	-848.4	256.428	0.0775	0.0928963
no	C18H36O2	-891	284.481	0.03525	0.0468753
no	C18H34O2	-764	282.465	0.1936	0.255624
no	C18H32O2	-634.7	280.45	0.1841	0.241346
no	C20H40O2	-1012.6	312.535	0.00105	0.0015339
				Sum	1 / 1

Table 6: JeJa50/50 Surrogate Fuel Blend Compositions[21],[22],[23], [24], [25].

IN LIB	Formula	Ass Enth	Molec.W	Mole Frac	Mass Frac
no	C9H12	-61.9	120.194	0.1171	0.0657916
no	C12H26	-364.3	170.337	0.13045	0.103889
no	C11H24	-327.2	156.311	0.09665	0.0706191
no	C11H22	-233.7	154.295	0.1558	0.11237
no	C14H28O2	-834.1	228.374	0.0085	0.0090735
no	C16H32O2	-848.4	256.428	0.0775	0.0928963
no	C18H36O2	-891	284.481	0.03525	0.0468753

no	C18H34O2	-764	282.465	0.1936	0.255624
no	C18H32O2	-634.7	280.45	0.1841	0.241346
no	C20H40O2	-1012.6	312.535	0.00105	0.0015339
Sum				1 / 1	

Table 7:Jeja75/25 Surrogate Fuel Blend Compositions[21],[22],[23] [24], [25].

IN LIB	Formula	Ass Enth	Molec.W	Mole Frac	Mass Frac
no	C9H12	-61.9	120.194	0.17565	0.115742
no	C12H26	-364.3	170.337	0.195675	0.182729
no	C11H24	-327.2	156.311	0.144975	0.124235
no	C11H22	-233.7	154.295	0.2337	0.197684
no	C14H28O2	-834.1	228.374	0.00425	0.0053210
no	C16H32O2	-848.4	256.428	0.03875	0.054475
no	C18H36O2	-891	284.481	0.017625	0.027488
no	C18H34O2	-764	282.465	0.0968	0.1499
no	C18H32O2	-634.7	280.45	0.09205	0.141527
no	C20H40O2	-1012.6	312.535	0.000525	0.0008995
Sum				1 / 1	

3. Results

3.1. Fuel Heating Value

Figure 1 illustrates the changes in Lower Heating Value (LHV) across various biofuel blending ratios with Jet A-1. The Je/Ja blend shows a peak LHV improvement of approximately 2.287% at 100% Jatropha. These findings align with those reported by Azami et al [2], who observed a similar trend in Jatropha-based fuel blends. This study implies that higher heating value can be obtained from higher proportion of Jatropha in biofuel blend.

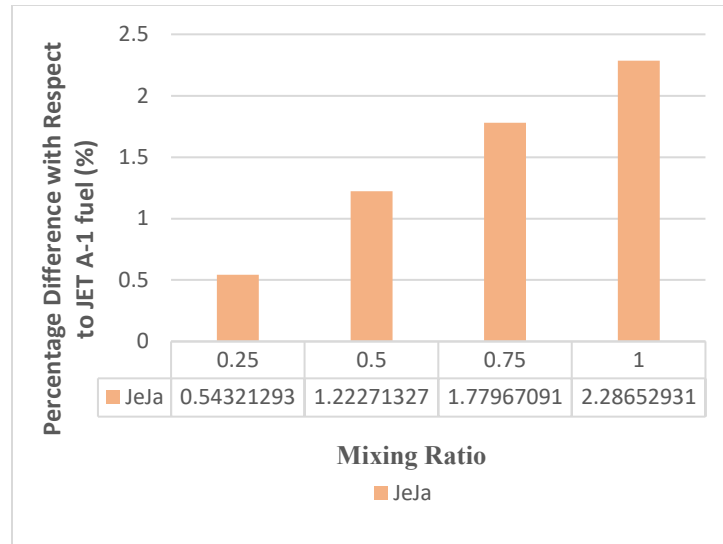


Figure 1: Illustrates the relative percentage difference in fuel heating value across various blend ratios, using neat Jet A-1 (ratio 0.0) as the reference baseline.

3.2. Design Point Performance Analysis

The design point simulation was conducted using the table provided in Table 3

3.2.1. Thrust

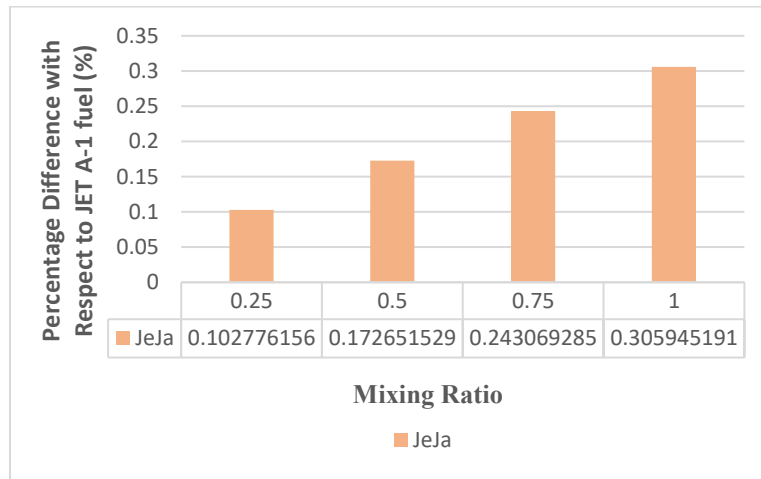


Figure 2: Thrust percentage difference with respect to pure Jet A-1 at different mixing ratios.

Figure 2 shows the simulated thrust data show that engine thrust increases with higher blend ratios for the biofuel blends, reaching a peak difference of approximately 0.306% at 100% Jatropha. At the 75/25 blend, the upward trend with blend ratio is consistent with existing studies on biofuel blends Mazlan et al, 2015 [26].

3.2.2. TSFC

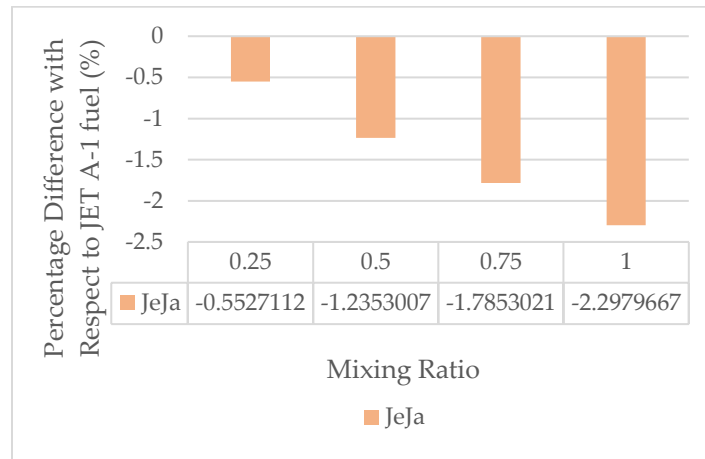


Figure 3: TSFC percentage difference with respect to pure Jet A-1 at different mixing ratios.

Figure 3 demonstrated that Jatropa based biofuel blends (JeJa) offer significant improvements in Thrust Specific Fuel Consumption across all tested mixing ratios, with the greatest benefits at higher Jatropa content reaching a reduction of approximately -2.298%. These findings did not align with previous research like a report by Sidibe et al, 2020 [27], probably because a diesel engine was used in their own study and they were focused on specific fuel consumption but it aligns with a publication by Azami et al, 2017 [2] and Mazlan et al, 2015 [26] which used Pythia gas turbine engine in their analysis.

3.2.3. Core Efficiency

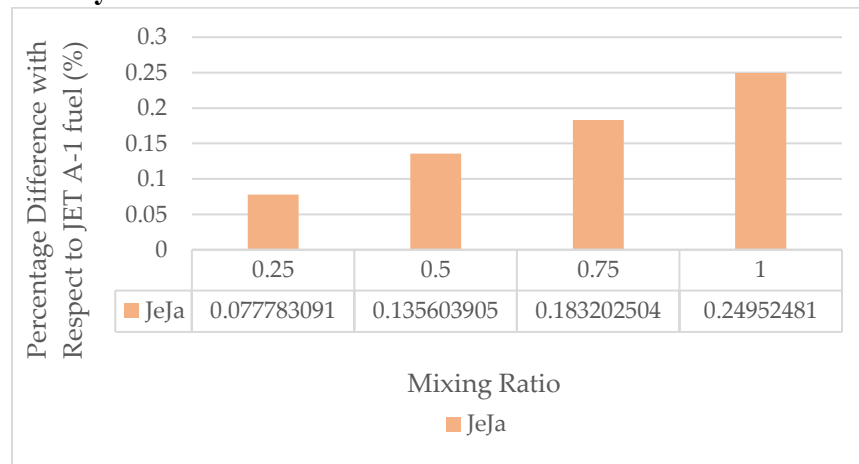


Figure 4: Core Efficiency percentage difference with respect to pure Jet A-1 at different mixing ratios.

Figure 4 show the engine's core thermal efficiency, showing an increase with increasing Jatropa blend ratio relative to Jet A-1. It gains rise from 0.0785 at a 0.25 blend (JeJa 75/25) to 0.136% at

0.50, 0.183 at 0.75 and a maximum value of 0.25% for 100% biofuel, these improvements indicate that higher bio-derived fractions slightly enhance core thermodynamic conversion efficiency.

3.2.3. NO_x emission

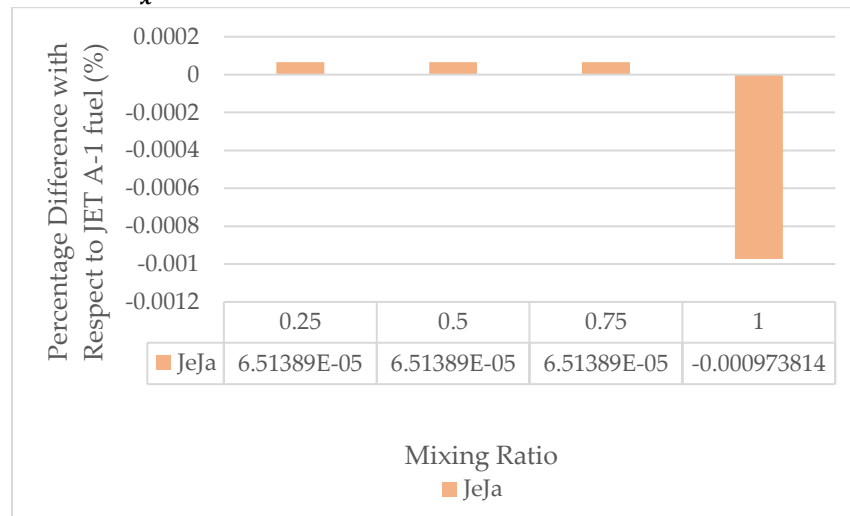


Figure 5: NO_x Severity Parameter variation with altitude.

Figure 5 shows the variation of the NO_x emission with respect to biofuel blend. It can be observed that the NO_x emission decreases with increase in the biofuel mixture or percentage with a value of -0.000974% at the 100% Jatropha having the highest reduction in emission, the changes are three to four orders of magnitude smaller than the corresponding changes in thrust, TSFC, and fuel flow, they are considered numerically negligible rather than evidence of a genuine NO_x benefit, and should not be interpreted as a monotonic trend with blend ratio.

3.2.4. Fuel Flow

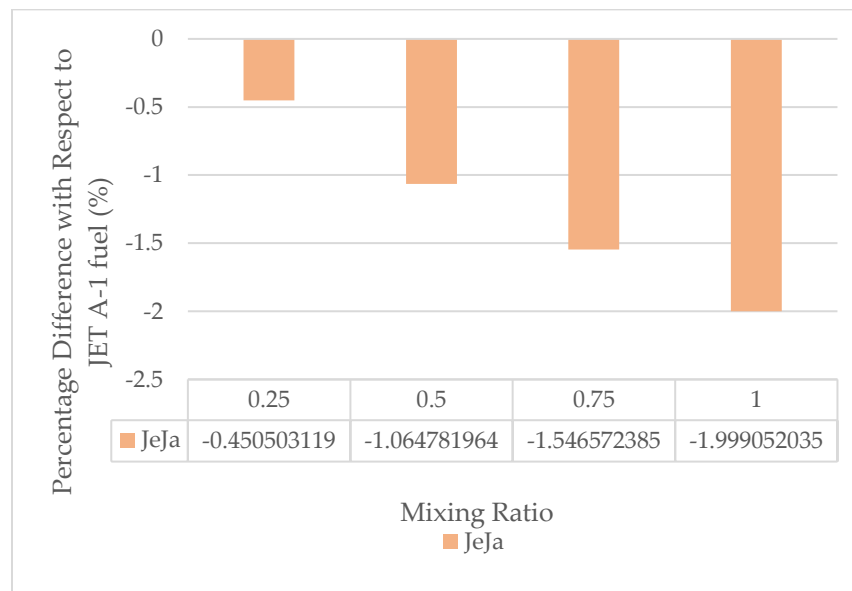


Figure 6: Fuel Flow percentage difference with respect to pure Jet A-1 at different mixing ratios.

The Fuel flow performance charts for the biofuel blends (as illustrated in Figure 6) show clear differences as the biofuel concentration rises. The JeJa blend exhibits a consistent decrease in mass fuel flow as the biofuel fraction increases, achieving a peak reduction of approximately -2.00% (-1.999 %) at 100% Jatropa (mixing ratio 1.0). This lower fuel flow requirement directly accounts for the improved thrust specific fuel consumption (TSFC) and confirms that the fuel metering system requires negligible recalibration to accommodate the alternative blend.

3.2.5. Core Efficiency

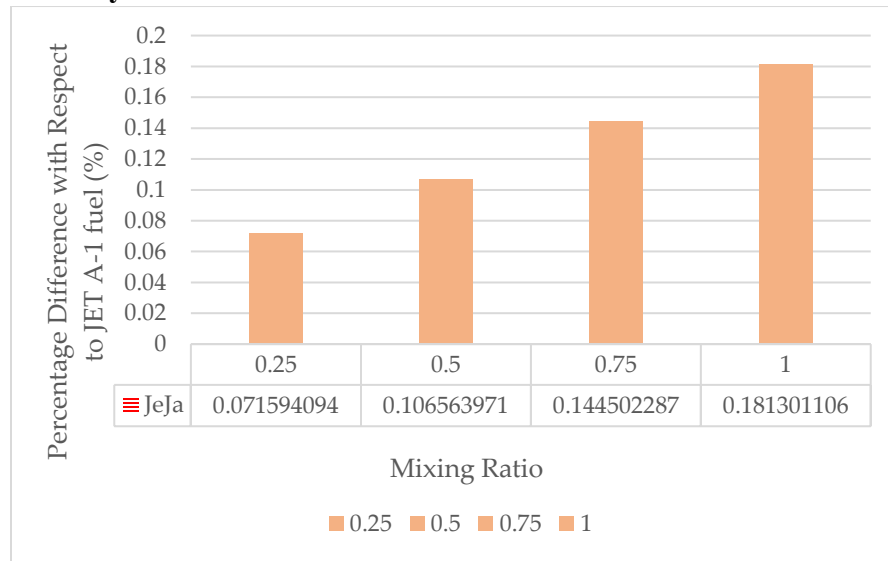


Figure 7: Exhaust Gas Temperature percentage difference with respect to pure Jet A-1 at different mixing ratios.

Figure 7 presents the percentage difference in Exhaust Gas Temperature (EGT) across various Jatropa biofuel blending ratios relative to baseline neat Jet A-1. The JeJa blend demonstrates a marginal, monotonic increase in EGT as the biofuel ratio increases, reaching a maximum elevation of approximately 0.181% at 100% Jatropa (mixing ratio 1.0). Because the peak temperature increase corresponds to an absolute change of only a few kelvins under standard cruise operating conditions, the blend poses negligible risk to turbine thermal limits or component service life.

3.3 Off design Point Performance Analysis

Under off-design conditions, the aircraft is brought up to its maximum speed while altitude varies from sea level (0 m) to 11,000 m. Performance metrics are plotted as lines on the primary axis, and percentage deviations from the baseline are shown as columns on the secondary axis.

3.3.1. Thrust Variation with Altitude

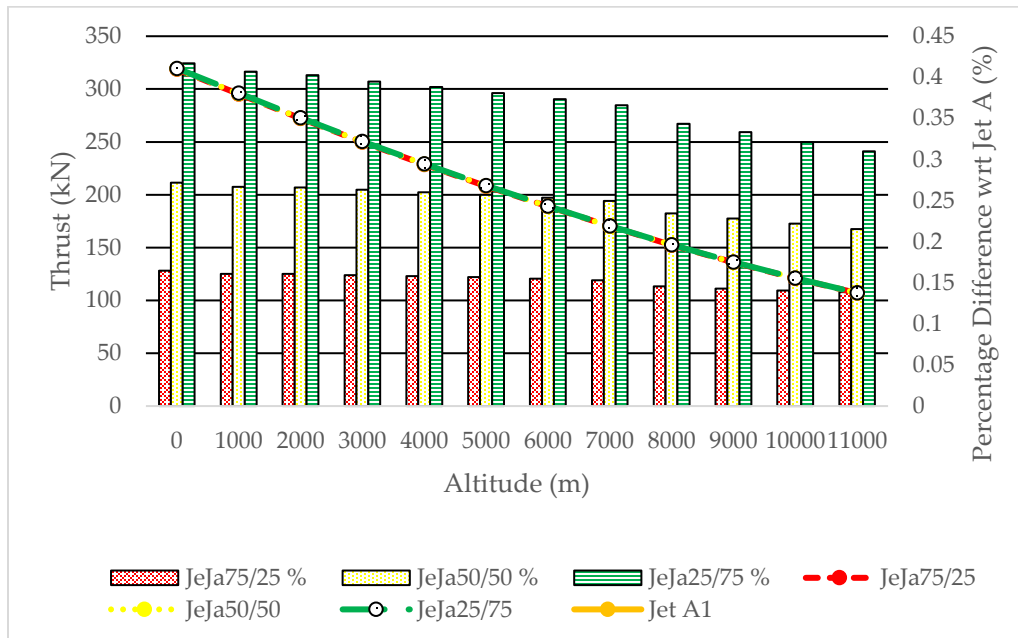


Figure 8: Variation of Thrust at different altitude.

Figure 8 displays a near negative linear variation in thrust shows the variation in the thrust generated at off design point at different altitude which aligns with expected aerodynamic principles due to decreasing air density at higher altitude. The variation of the thrust of generated by the biofuels compared with the Jet A-1 as seen shows a difference in thrust, it decreases with altitude dropping from approximately 0.41% at sea level to 0.14% at 11,000 m, hence we can say that the thrust of the blends reduces as altitude increases.

3.3.2. TSFC Variation against Altitude

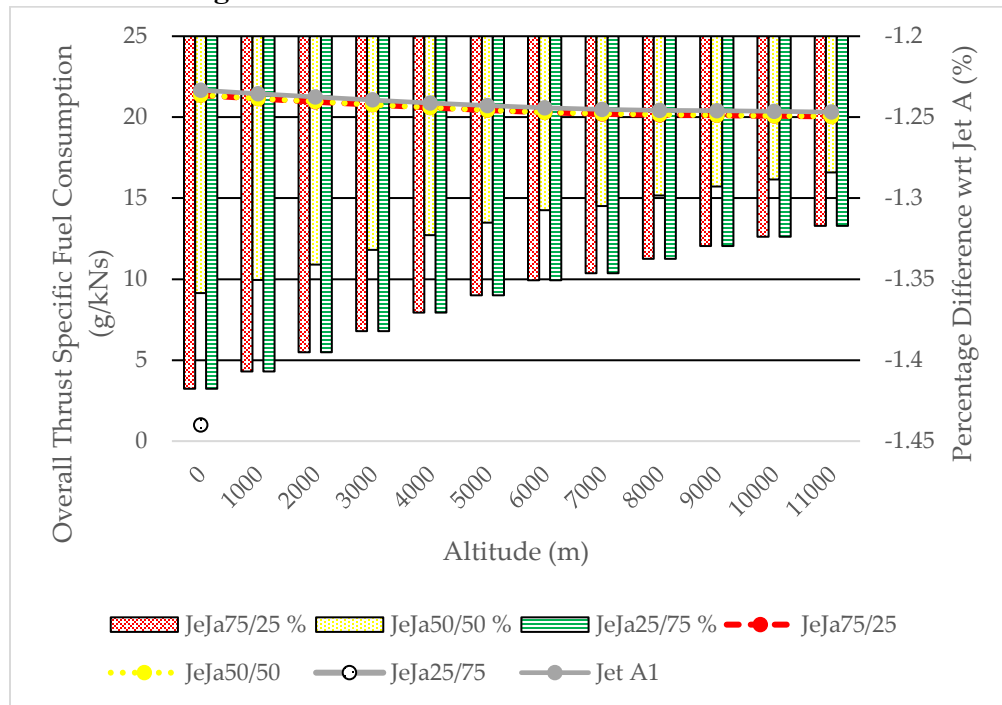


Figure 9: Variation of TSFC at different altitude.

The graph in Figure 9 demonstrates that TSFC decreases consistently with altitude for all fuel types, from approximately 21.2 – 21.8g/kNs at sea level to 20.0 – 20.3 g/kNs at 11,000 meters whereas, the percentage change with the Jet-A1 increases from – (1.359 – 1.418) % to –(1.284 – 1.317)%. This trend reflects improved fuel efficiency at higher altitudes due to reduced air density and optimized engine operating conditions.

3.3.3. Thermal Efficiency

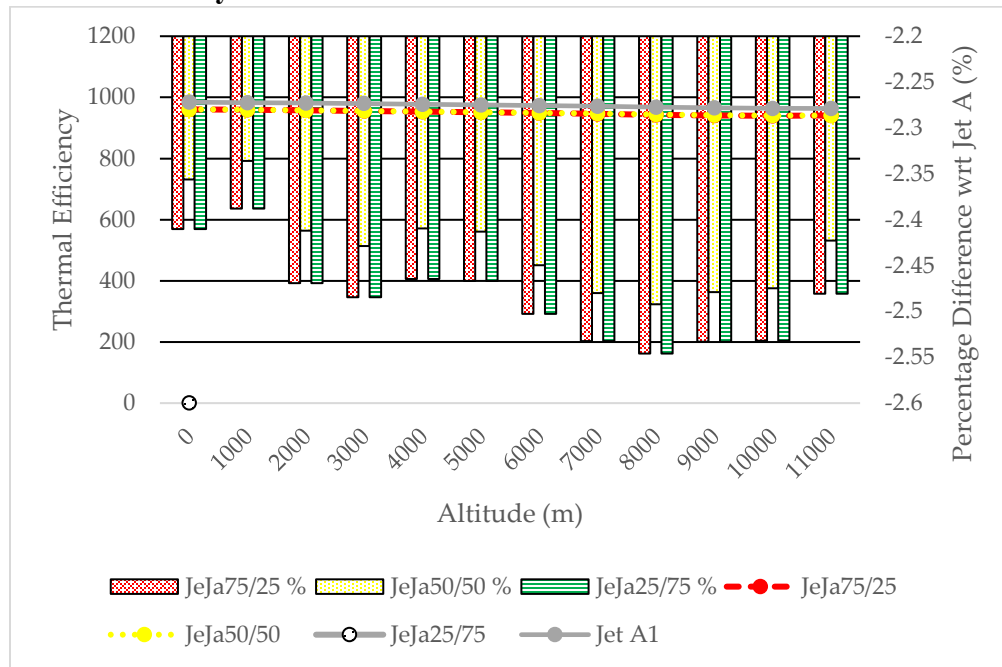


Figure 10: Variation of Thermal Efficiency with altitude.

Figure. 10 shows the variation of the thermal efficiency performance metrics against altitude from sea level to 11000m. It is observed that Conventional Jet A-1 maintains a slightly higher value compared to the Jatropha biofuel blends throughout the flight envelope, reflecting a marginal percentage difference of approximately -2.25% to -2.55%.

3.3.4. Fuel Flow

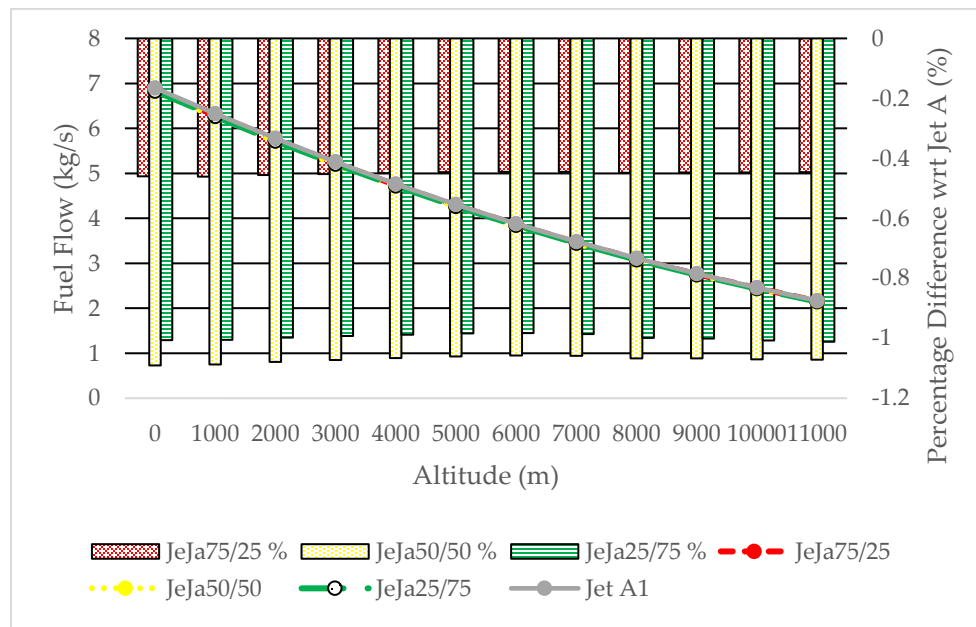


Figure 11: Variation of fuel flow with altitude.

Figure 11 shows the variation of the fuel flow with altitude; the fuel flow decreases with altitude in a almost linear manner from 6.84kg/s at sea level to 2.18kg/s 11000m with an overall reduction of nearly 68%. It is also observed that the difference in fuel flow of the biofuel is slightly minimal compared to that of Jet A-1 which did not exceed the -1.1%. Across the different altitudes, the biofuel blends show slightly lower fuel flow rates than baseline Jet A-1. This reduction in fuel mass flow at equivalent operating account for the improved TSFC.

3.3.5. Exhaust Gas Temperature with Altitude

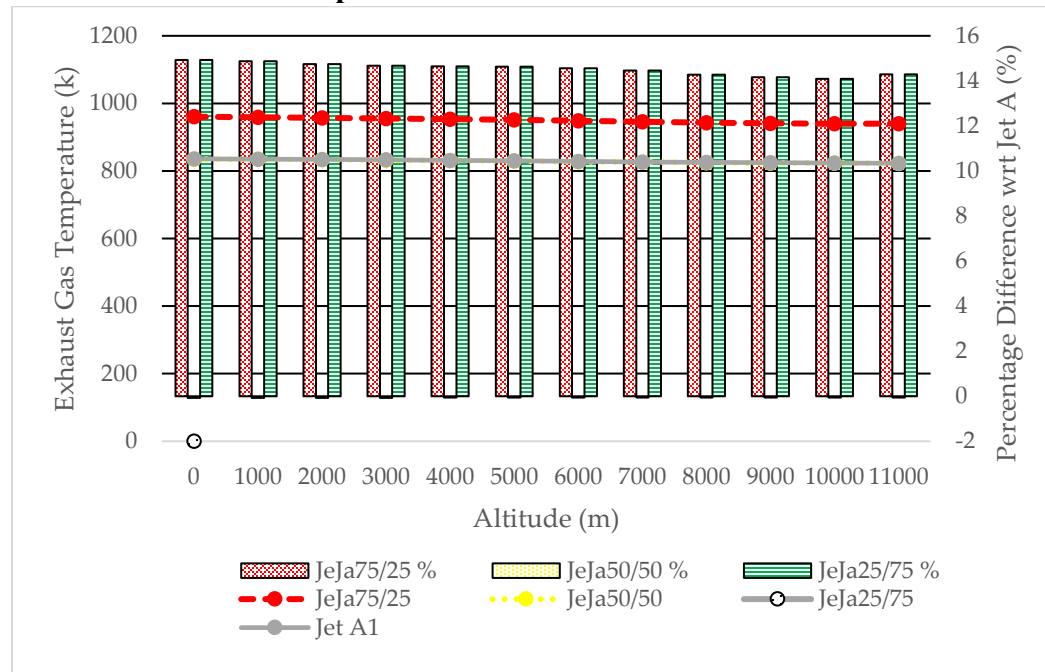


Figure 12: Variation of exhaust temperature with altitude.

The exhaust gas temperature variation with altitude is described in Figure 12. It is observed that the exhaust gas temperature is relatively stable with altitude, while JeJa 50/50 and JeJa 25/75 align closely with Jet-A1 between 820k, 840k, JeJa 75/25 produces the highest exhaust temperature across the entire altitude range (940K to 960K), this notable thermal rise suggests that higher blend concentrations of this composition would subject the exhaust ducting and nozzle components to increased thermal loads relative to baseline Jet A-1.

3.3.6. Emission (Severity Parameter)

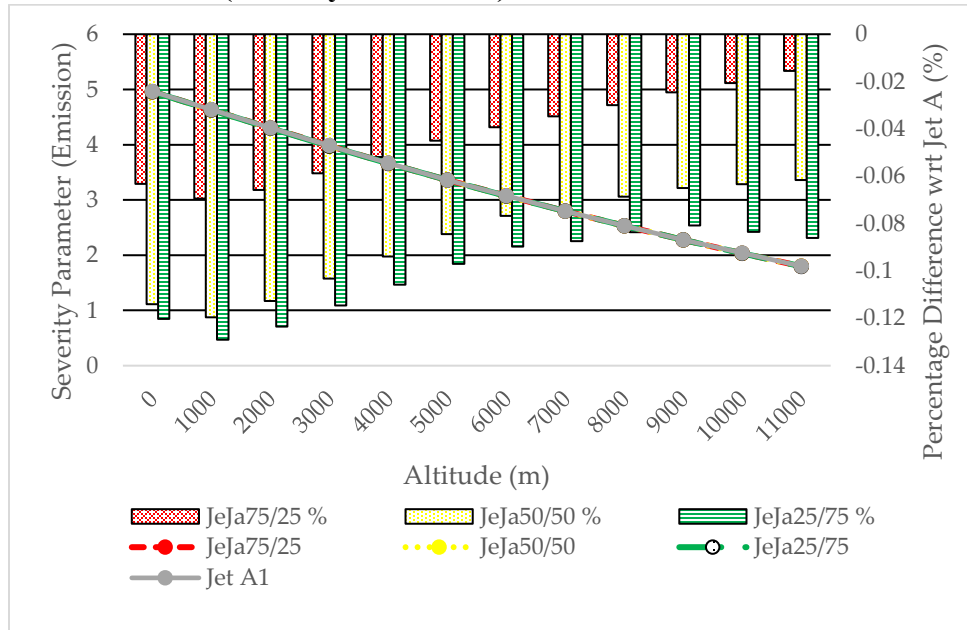


Figure 13: Variation of Emission (Severity Parameter) at different altitude.

Figure 13 represents the variation of the Emission (Severity Parameter) with altitude showing that the NO_x emission decreases with increase in altitude however this variation follows a near-linear pattern dropping from 4.92 at sea level to 1.80 at 11000m due to reduce combustor loading. It was observed that the Jet A-1 remains marginal (within -0.002% to -0.13%), with higher blend fractions (JeJa 25/75 and JeJa 50/50), providing more reduction than JeJa 75/25.

4. Conclusions

This simulation result shows the possibility of utilizing the biofuel blend in aviation. The results show that Jatropha oil can be used to reduce emission, reduce thrust specific fuel consumption and still generate higher volume of thrust. The study shows the practical application of biofuel engine in Aviation for the RB211-524G2 turbofan Engine, the performance, fuel efficiency, and emissions characteristic of the turbofan engine when operated with Jatropha biodiesel blends can achieve in line with the objectives and implemented in the future via further research.

Abbreviations

The following abbreviations are used in this manuscript:

Ass Enth	Assigned Enthalpy
CEA	Chemical Equilibrium with Applications
EGT	Exhaust Gas Temperature
GHG	Greenhouse Gas
Jet A-1	Jet A-1 Aviation Turbine Fuel

LHV	Lower Heating Value
Mass Frac	Mass Fraction
Mole Frac	Mole Fraction
Molec.W	Molecular Weight
NASA	National Aeronautics and Space Administration
NO _x	Oxides of Nitrogen
RB211- 524	Rolls-Royce RB211-524 Turbofan Engine
SAF	Sustainable Aviation Fuel
TSFC	Thrust-Specific Fuel Consumption
S_{NO_x}	NO_x Severity Parameter
P_3	Pressure at the last compressor Exit
T_3	Temperature at the last compressor exit
war	Water-air-ratio
F	Thrust
A_8	Area of the nozzle throat.
P_{amb}	ambient pressure.
P_8	pressure at nozzle exit.
γ	adiabatic index
λ	air-fuel ratio
$TSFC$	Thrust Specific Fuel Consumption
f	fuel air ratio
F_T	Thrust
$\dot{m}_f$	fuel flow rate
R	Range
$\frac{L}{D}$	Lift-to-Drag ratio

V_{∞} True airspeed of the aircraft
 W_0 is the gross weight (with full fuel tanks) of the aircraft
 W_1 the weight with the aircraft fuel tanks empty.

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