The Effect of Flight and Design Parameters of a Turbofan Engine on Global Warming Potential

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Abstract. Anthropogenic global warming is caused by human beings as a result of fuel combustion process used in energy production, transportation, residential heating etc. Fossil fuels after combustion generate gases such as CO₂, H₂O, NOx, SOx, CO etc. Those gases form a greenhouse effect and causes global warming. For a sustainable world there is a need to limit those greenhouse gases. Transportation vehicles also consume fossil fuels and aviation is a part of that. Aircraft engines emit exhaust gases during flight and ground operations. Turbofan engine is the most common type in commercial aviation today. Turboprop, turbojet and piston engines constitute a smaller percentage in the sector. In this study, in order to reduce the environmental impact of aviation, a turbofan engine related exhaust gas emission was calculated for different input parameters of design and operation. Global warming potential (GWP) parameter was analysed as a sensitivity study with respect to input parameters. A +/-5% change was considered for input parameters and effects on GWP were presented in the order of magnitude and importance. Results obtained in this study have practical implications for engine designers and operators to potentially reduce the GWP for a sustainable world.

Keywords: Global warming potential; turbofan engine; greenhouse gas emissions; cycle analysis; sustainability

1. Introduction

Anthropogenic global warming is the increase of Earth’s average temperature due to human activities in the long term. CO₂ is the main contributor of global warming which is a byproduct of combustion of fossil fuels such as coal, oil, natural gas etc. In other words, fossil fuel combustion generates heat-trapping gases and when these gases are released into atmosphere; more heat is stored which causes global temperature increase in Earth’s atmosphere. Other contributors are methane (CH₄), nitrous oxides (NOx), ozone (O₃) and also water vapor (H₂O) [1], [2]. Climate change and global warming is a big risk for society [3], [4]. In 2018, CO₂ emissions have reached a maximum value of 37.1 billion tons [5]. GHG emissions are predicted to increase 50% more compared to today’s value in 2050, mostly from energy needs of growing population [4]. Therefore, we need more efforts in finding solutions to reduce emissions.

Transportation vehicles also consume fossil fuels and aviation is a part of that. Aircraft engines emit exhaust gases during flight and ground operations. On the reduction of greenhouse gas emissions there is a lot of research and development in aviation sector. Whellens and Singh [6] studied propulsion system optimisation for minimum Global Warming Potential. Jelinek et al. [7] developed an advanced emissions...
model to estimate aviation emissions and fuel burn. Jungbluth and Meili [8] offered recommendations for calculation of the global warming potential of aviation including the radiative forcing index. Şöhret et al. [9], [10] presented environment-friendly engine selection methodology for aerial vehicles and also mathematical modelling for carbon dioxide equivalent prediction of greenhouse gases emitted from a small scale turbojet engine. Wang et al. [11] investigated flight operation and airframe design for tradeoff between cost and environmental impact. Berton and Guynn [12] performed multi-objective optimization of turbofan design parameters for an advanced, single-aisle transport aircraft. Wasiuk et al. [13] presented an aircraft performance model implementation for the estimation of global and regional commercial aviation fuel burn and emissions. Jakovljević et al. [14] calculated carbon dioxide emission during the life cycle of turbofan aircraft. Dinc [15–17] studied NOx emission of aircraft engines for LTO and GWP for a complete flight cycle. Becker [18] studied exhaust emissions characteristics for a general aviation light-aircraft. Pagoni and Psaraki-Kalouptsidi [19] performed calculations of aircraft fuel consumption and CO2 emissions based on path profile estimation by clustering and registration. Diehl and Biaglow [20] performs measurements of gaseous emissions from a turbofan engine.

Turbofan engine is the most common type in commercial aviation today. Turboprop, turbojet and piston engines constitute a smaller percentage in the sector. In this study, in order to reduce the environmental impact of aviation, a turbofan engine related exhaust gas emissions were calculated for different input parameters on a JT9D-7J turbofan engine model. Global warming potential values were calculated for a range of selected design and flight parameters such as altitude, speed, turbine inlet temperature, compressor pressure ratio, compressor efficiency, turbine efficiency etc. Global warming potential (GWP) parameter was analyzed as a sensitivity study with respect to input parameters. A +/-5% change was considered for input parameters and effects on GWP were presented.

2. Materials and methods
1.1 Turbofan Engine Performance Model
In this study, cycle analysis was done for 222 kN (50000 lb) class JT9D-7J turbofan engine [21] which is typically used in B747 commercial aircraft (Figure 1). The cycle analysis results include the total pressure and temperature values at every engine station (for every component of the engine e.g. compressor, combustor, turbine, nozzle etc.) and also engine performance values such as shaft power output, specific fuel consumption, fuel flow rate etc. Then, exhaust emissions of engine were calculated from those values. All the analysis was done for cruise condition which is 0.85 Mach speed and 10668 m flight altitude since the exhaust emissions are mostly produced at cruise. At cruise flight condition, data from literature was 49.06 kN for engine thrust and 17.8744 g/(kN.s) for thrust specific fuel consumption [21].

Input values were collected from different sources and some assumptions were made if no data is available. Thus, total set of data used in the cycle analysis calculations which are given in Table 1. Results were found to be very close to literature data of JT9D-7J engine and a general comparison was given in Table 2.

![Figure 1. (a) JT9D-7J turbofan engine, (b) B747 aircraft](image_url)
Table 1. Assumed design input parameters for JT9D-7J turbofan engine

| Input parameter | Definition | Assumed Value |
|-----------------|------------|---------------|
| $\Delta P_{in}$ | intake total pressure loss | 0.01          |
| $\Delta P_{pipe}$ | total pressure loss of the low pressure turbine jet pipe | 0.01          |
| FHV | Fuel heating value (MJ/kg) | 43.124        |
| $h$ | Flight altitude (km) | 10.668        |
| $M$ | Flight speed (Mach) | 0.85          |
| $m$ | inlet corrected air mass flow rate (kg/s) | 721.2         |
| $N_{cd}$ | nozzle discharge coefficient | 1            |
| $T_4$ | total temperature at turbine entry (K) | 1390          |
| $\varepsilon_{2a}$ | cooling air ratio for high pressure turbine rotor | 0.06          |
| $\varepsilon_{3}$ | cooling air ratio nozzle guide vanes | 0.05          |
| $\eta_b$ | combustor efficiency | 0.99          |
| $\eta_{C}$ | compressor isentropic efficiency | 0.9           |
| $\eta_{FB}$ | booster isentropic efficiency | 0.9           |
| $\eta_{HPT}$ | high pressure turbine isentropic efficiency | 0.91          |
| $\eta_{m}$ | shaft mechanical efficiency | 0.99          |
| $\eta_{PT}$ | power turbine isentropic efficiency | 0.9           |
| $\Pi_B$ | Burner design pressure ratio | 9             |
| $\Pi_C$ | compressor total pressure ratio | 2.61          |
| $\Pi_{FB}$ | booster total pressure ratio |               |

Table 2 Comparison of cruise performance parameters for JT9D-7J turbofan engine

| Parameter | Literature Data* | Calculated Value | Deviation (%) |
|-----------|------------------|------------------|---------------|
| Thrust at cruise (kN)** | 49.06 | 49.11 | 0.09%         |
| TSFC at cruise (g/(kN.s))** | 17.8744 | 17.8886 | 0.07%         |

*Source: [21]  
**at 0.85 Mach speed and 10668 m flight altitude

1.2 Global Warming Potential Calculations

Total GWP value is the sum of the individual contributions of CO$_2$, H$_2$O and NOx. The smaller effects of CO, HC were neglected in this study. Emissions metrics are proportional to fuel flow and values are 3.155 (kg/kg fuel) for CO$_2$ and 1.237 (kg/kg fuel) for H$_2$O [22]. In other words, for each kilogram of fuel burned, 3.155 kilogram of CO$_2$ and 1.237 kilogram of H$_2$O are generated during combustion process.

\[
GWP_{\text{total}} = GWP_{\text{CO}_2} + GWP_{\text{H}_2\text{O}} + GWP_{\text{NOx}}
\]

(1)

\[
GWP_{\text{CO}_2} = 3.155 \ m_{\text{fuel}}
\]

(2)

\[
GWP_{\text{H}_2\text{O}} = 1.237 \ m_{\text{fuel}}
\]

(3)

\[
GWP_{\text{NOx}} = EI_{\text{NOx}} \ m_{\text{fuel}}
\]

(4)

where $EI_{\text{NOx}}$ is NOx emission index and $m_{\text{fuel}}$ is the mass of fuel to be burned. For prediction of $EI_{\text{NOx}}$, ‘P3T3’ (compressor discharge pressure and temperature) method can be used in general and test data is also needed for validation. The NOx Severity Parameter $S_{\text{NOx}}$ can be defined by Eq(5) [23]. The following equations were used in the prediction of NOx in this study.

\[
S_{\text{NOx}} = \left( \frac{P_3}{2965 \text{ kPa}} \right)^{0.4} e^\frac{(T_3-826 \text{ K}) + 0.29-100 \times \text{warp}}{53.2}
\]

(5)

\[
EI \sim S_{\text{NOx}}
\]

(6)
\[ EI_{NOx} = C \left( \frac{P_t}{2965 \text{ kPa}} \right)^{0.4} e^{\left( \frac{T_3 - 826 \text{ K}}{194 \text{ K}} + \frac{6.29 \times 100 \text{ war}}{53.2} \right)} \]  

(7)

The NOx Emission Index \( EI_{NOx} \) (g/kg fuel) increases linearly with the NOx severity parameter where C is a constant for the specific engine. Schulte et al. [24] performed NOx measurements on several aircraft and engines during flight. They provided flight test data for JT9D-7J turbofan engine on B747-200B aircraft during London - Washington flight at 0.85 Mach and 10058 m of altitude. The measurement for NOx emission index \( EI_{NOx} \) was 23.7 (g/kg fuel) for this cruise flight conditions. From this data, C constant was calculated to be 74.5 in Eq (7).

3. Results and discussion

According to the methodology described above, GWP values were calculated for the baseline engine initially. Then, the some of the design parameters were selected and were changed by ±5%. The effect of ±5% change on GWP were calculated and tabulated in Table 3. In order to make better comparisons, GWP values were calculated in (kg/(kN.s)) similar to TSFC, because engine thrust varies due to the changes in input parameters.

In the first place, the total GWP value for baseline engine can be seen 78.952 (kg/(kN.s)). CO2 constitutes the majority of the GWP with a value of 56.439 (kg/(kN.s)). Then water vapor (H2O) with 22.128 (kg/(kN.s)) value comes second. Smallest contributor is NOx with a value of 0.2891 (kg/(kN.s)). Except for NOx, CO2 and H2O emissions have similar trend with TSFC (thrust specific fuel consumption) in total GWP values. Therefore, any effort to decrease in fuel consumption would decrease GWP (except for NOx value).

In Table 3, the effects of individual parameters were evaluated. Those parameters are \( T_4, \Pi_{FB}, \Pi_C, \eta_{FB}, \eta_C, \eta_{PT}, \eta_{HPT}, \text{ and } h \) (km), Mach number. The results are also depicted in Figures 2-10.

Most effective parameter was calculated to be \( T_4 \) (total temperature at turbine entry) and the 2nd effect comes from the Mach number as shown in Figure 2. Thirdly, \( \eta_{PT} \) (power turbine isentropic efficiency), 4th \( \eta_{HPT} \) were depicted in Figure 3. Then \( \Pi_C \) and \( \Pi_{FB} \) as given in Figure 4. Lastly, \( \eta_C \) and \( \eta_{FB} \) are less effective among the investigated parameters.

![Figure 2. Effect of parameters on total GWP (%) a) \( T_4 \), b) Mach number](image)
Figure 3. Effect of parameters on total GWP (%) a) $\eta_{PT}$, b) $\eta_{HPT}$

Figure 4. Effect of parameters on total GWP (%) a) $\Pi_C$, b) $\Pi_{FB}$

Figure 5. Effect of parameters on total GWP (%) a) $\eta_C$, b) $\eta_{FB}$
Table 3. Effect of design and flight parameters on GWP.

| Case No | Design and Flight Parameters | Output Parameters |
|---------|------------------------------|-------------------|
|         | Name                         | Baseline Value    | Modified Value (+5%) | Thrust (kN) | TSFC (g/(kN.s)) | Fuel flow (kg/s) | CO2 (g/(kN.s)) | H2O (g/(kN.s)) | NOx severity | NOx (g/(kN.s)) | GWP (g/(kN.s)) | Change |
| 1       | Τ₄ (K)                       | 1390              | 1320.5             | 45.19       | 17.40           | 0.786            | 54.896         | 21.524         | 0.2891       | 0.3853       | 78.985         | -2.73% |
| 2       | Π₈                           | 2.61              | 2.4795             | 49.31       | 18.04           | 0.889            | 56.903         | 22.310         | 0.2693       | 0.3619       | 79.607         | 0.79%  |
| 3       | Π₉                           | 2.61              | 2.7405             | 48.90       | 17.75           | 0.868            | 56.004         | 21.958         | 0.3095       | 0.4093       | 78.407         | -0.73% |
| 4       | Π₉                           | 9                 | 8.55               | 49.30       | 18.03           | 0.889            | 56.899         | 22.309         | 0.2696       | 0.3622       | 79.602         | 0.78%  |
| 5       | Π₉                           | 9                 | 9.45               | 48.91       | 17.75           | 0.868            | 56.008         | 21.959         | 0.3091       | 0.3748       | 79.313         | 0.42%  |
| 6       | Π₉                           | 0.9               | 0.945              | 49.74       | 18.04           | 0.860            | 56.915         | 22.315         | 0.3143       | 0.4224       | 79.688         | 0.89%  |
| 7       | Π₉                           | 0.9               | 0.945              | 50.30       | 17.79           | 0.895            | 56.125         | 22.005         | 0.2680       | 0.3552       | 78.516         | -0.59% |
| 8       | Π₉                           | 0.9               | 0.945              | 50.30       | 17.79           | 0.895            | 56.125         | 22.005         | 0.2680       | 0.3552       | 78.516         | -0.59% |
| 9       | Π₉                           | 0.9               | 0.945              | 49.74       | 18.04           | 0.867            | 56.658         | 22.159         | 0.3020       | 0.4041       | 79.313         | 0.42%  |
| 10      | Π₉                           | 0.9               | 0.945              | 49.74       | 18.04           | 0.867            | 56.658         | 22.159         | 0.3020       | 0.4041       | 79.313         | 0.42%  |
| 11      | Π₉                           | 0.9               | 0.945              | 49.74       | 18.04           | 0.867            | 56.658         | 22.159         | 0.3020       | 0.4041       | 79.313         | 0.42%  |
| 12      | Π₉                           | 0.9               | 0.945              | 49.74       | 18.04           | 0.867            | 56.658         | 22.159         | 0.3020       | 0.4041       | 79.313         | 0.42%  |
| 13      | Π₉                           | 0.9               | 0.945              | 49.74       | 18.04           | 0.867            | 56.658         | 22.159         | 0.3020       | 0.4041       | 79.313         | 0.42%  |
| 14      | Π₉                           | 10.668            | 10.135             | 52.21       | 17.90           | 0.935            | 56.468         | 22.147         | 0.3143       | 0.4192       | 79.089         | 0.13%  |
| 15      | Π₉                           | 10.668            | 11.201             | 45.75       | 17.89           | 0.818            | 56.428         | 22.124         | 0.2709       | 0.3610       | 78.944         | -0.05% |
| 16      | Π₉                           | 10.668            | 11.201             | 45.75       | 17.89           | 0.818            | 56.428         | 22.124         | 0.2709       | 0.3610       | 78.944         | -0.05% |
| 17      | Π₉                           | 0.85              | 0.8075             | 48.68       | 17.56           | 0.855            | 55.395         | 21.719         | 0.2731       | 0.3572       | 77.501         | -1.88% |
| 18      | Π₉                           | 0.85              | 0.8925             | 49.59       | 18.22           | 0.904            | 57.493         | 22.541         | 0.3068       | 0.4165       | 80.487         | 1.90%  |
4. Conclusion
In this study, the effects of selected input parameters were investigated parametrically on global warming potential. It was presented the magnitude of effects of $T_4$ (total temperature at turbine entry), flight Mach number, $\eta_{PT}$ (power turbine isentropic efficiency), $\Pi_C$ (compressor pressure ratio) and $\Pi_{FB}$ (booster pressure ratio), $\eta_C$ (compressor isentropic efficiency), and $\eta_{FB}$ (booster isentropic efficiency) on GWP. Results can be used for engine designers and airline operators as a guide to reduce GWP. Therefore results can support the efforts to reduce greenhouse gases emissions for a sustainable world.

Nomenclature

| Symbol | Description |
|--------|-------------|
| CO     | carbon monoxide |
| CO₂    | carbon dioxide |
| EINOx  | NOx emission index (g/kg fuel) |
| FHV    | jet fuel heating value (MJ/kg) |
| GWP    | global warming potential |
| h      | altitude (km) |
| H₂O    | water vapor |
| HC     | unburned hydrocarbons |
| HPT    | high pressure turbine |
| m      | inlet corrected air mass flow rate (kg/s) |
| NOx    | nitrogen oxides |
| $P_{amb}$ | ambient pressure (kPa) |
| PSFC   | power specific fuel consumption |
| PWSD   | shaft power delivered |
| SNOx   | NOx severity parameter |
| SOx    | sulfur oxides |
| $T_4$  | total temperature at turbine entry (K) |
| $T_{amb}$ | ambient temperature (K) |

Greek Letters

| Symbol | Description |
|--------|-------------|
| $\varepsilon_{2a}$ | cooling air ratio for HPT rotor |
| $\varepsilon_3$ | cooling air ratio nozzle guide vanes |
| $\eta_b$ | combustor efficiency |
| $\eta_C$ | compressor isentropic efficiency |
| $\eta_{FB}$ | booster isentropic efficiency |
| $\eta_{HPT}$ | isentropic efficiency |
| $\eta_m$ | shaft mechanical efficiency |
| $\eta_{PT}$ | power turbine isentropic efficiency |
| $\Pi_B$ | combustor total pressure ratio |
| $\Pi_C$ | compressor total pressure ratio |
| $\Pi_{FB}$ | booster total pressure ratio |

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