Sustainability assessment of turbofan engine with mixed exhaust through exergetic approach

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Abstract. In this study, the theory, methods and example application are described for a CF6 high-bypass turbofan engine with mixed exhaust flow based on exergo-sustainable point of view. To determine exergetic sustainability index, the turbofan engine has to undergo detailed exergy analysis. The sustainability indicators reviewed here are the overall exergy efficiency of the system, waste exergy ratio, exergy destruction factor, environmental effect factor and the exergetic sustainability index. The results obtained for these parameters are 26.9%, 73.1%, 38.6%, 2.72 and 0.37, respectively, for the maximum take-off condition of the engine. These results would be useful to better understand the connection between the propulsion system parameters and their impact to the environment in order to make it more sustainable for future development.

1. Introduction
The civil aviation industry plays a major role in the current world economy with more than 2 billion people travel around the world annually and 23,000 aircraft in commercial industry [1]. Such a rapid growth of this industry also causes an unavoidably increase in the aviation greenhouse gas emissions. One of the proposed solutions to encounter this is by using energy and exergy with better efficiency, in hopes for better reduction of the pollutant emissions. Exergy analysis is a useful performance analysis method and the determination of the irreversibility rates is based on the calculation of isentropy. By increasing the efficiency, it is hoped that there will be less demand of fuel and consequently less waste to be released. Both engine fuel consumption and environment impact due to aircraft play an important role to attain sustainable development with environmental protection. Hence, extra efforts with many approaches have been applied in aviation industry over the years to better understand and improve the performance characteristics of aircraft.

An aircraft is a complicated system that consists of several parts that are exposed to environmental conditions during operation, which are often varying and unstable. The aviation industry has started to construct remarkably complex aircraft designs with many mixed systems that create demands for more data acquisition to estimate the overall system performance. Many methods have been proposed since the very beginning of this industry to study the flight performance but it is agreed that a common basis must be applied when assessing different approaches in aircraft design, particularly when constructing new systems. The application of exergy analysis method will be very helpful to do comparative study between the different system designs and this is shown by the increasing number of papers concerning aircraft engines in the last four years [2].
The studies concerning energy and exergy analysis of turbofan engine have already began since a decade ago. About 47% of exergy-based analyses have been linked to aircraft engines, mostly deal on turbofan engines and around 22% of them discussed on turbojet engines [2]. The first few conducted studies have used hydrogen as fuel replacing kerosene to run the engine [3,4], which is shown to have a great impact in reducing Specific Fuel Consumption (SFC) rate by as much as 39.2% [3]. Moreover, the exergy efficiency is inversely proportional with altitude due to decreasing value of temperature [4]. In the meantime, several studies have also been conducted using either Jet-A1 or JP8 as the fuel [1, 5-9]. Most of these studies cover not only the thermodynamic analysis part, but also the economic [5, 7] and sustainability factors [1, 9]. However, all of them take a turbofan engine with separate exhaust as the case study. According to one of the studies, turbofan engine with mixed exhaust and no afterburner would give the optimized value of SFC [10]. In another study, fan and core engine exhausts are shown to have the highest potential improvement rate based on exergy analysis performed, which means that the focus in future development should be placed on these two components since they still have higher chances to be improved for better performance [6].

Sustainability has been linked to issues of environmental, economic and social dimensions toward responsible management of resources. A higher sustainability index indicates a low waste exergy ratio and low environmental effect factor. In this study, a turbofan engine with mixed exhaust is introduced and, its performance and sustainability index based on exergy is analyzed. The results are compared to the exergy analysis of turbofan with separate exhaust engine done by previous researchers.

2. System Description
The schematic of a turbofan engine that consists of a fan, a low-pressure compressor (LPC), a high-pressure compressor (HPC), an annular combustion chamber (CC), a low-pressure turbine (LPT) and a high-pressure turbine (HPT) is illustrated in Figure 1. The fan, compressors and turbines are taken to be adiabatic in this study. The first drive shaft is the high pressure (HP) system that links the HPT and HPC. Meanwhile, the second shaft is the low pressure (LP) system that links the LPT to the LPC and the fan. Because of these two systems, this engine is described as a two-spool turbofan engine. In the turbofan with mixed exhaust engine, after initially compressed in the fan, the “cold air” is compressed again with the “hot air” coming out of the turbine. Eventually both flows of air are mixed in a mixer to attain the same static pressure before entering the nozzle for expansion.

![Figure 1: Schematic of CF6 turbofan engine [6]](image)

The intake air mass flow rate of 679.2kg/s (or 16.6%) is used in the combustion process along with 2.2kg/s of fuel. The “cold air”, which flows through the fan and exhaust, constitutes around 82.4% of the intake air flow. Meanwhile, the bleed air flowing out from HPC to HPT quantifies for 1% of this
air flow, which is mainly used for cooling of the first stage of HPT. The gas flows in the engine are assumed to behave ideally. The maximum engine take-off thrust is 185.05kN with an inlet air speed of 147m/s. For this study, kerosene is used and it has a specific chemical exergy of 45.8MJ/kg \[11\]. The air composition at the engine inlet is taken from Ref. \[12\]. The combustion equation involved can be expressed in terms of mole fractions of each gas as in Equation 1.

$$\begin{align*}
0.013174C_{12}H_{23} + 3.963210(0.7748N_2 + 0.2059O_2 + 0.0003CO_2 + 0.019H_2O) &\to \\
0.159277CO_2 + 0.226802H_2O + 0.582186O_2 + 3.070695N_2
\end{align*}$$

(1)

3. Exergy Analysis of Turbofan Engine

Only physical and chemical exergies are considered inside each component, excluding the exhaust part due to the high velocity of discharging flows at the exit. Moreover, potential exergy is also neglected since there is no significant height difference between intake and exit of the engine. Specific physical exergy is defined by Equation 2 \[13\], where $\bar{h}$ and $\bar{s}$ are the specific molar enthalpy and specific molar entropy, respectively, with the reference temperature is set as the ambient.

$$\bar{e}_x_{ph,k} = \bar{h}_k - \bar{h}_0 - T_0(\bar{s}_k - \bar{s}_0) \tag{2}$$

Furthermore, the chemical exergy is defined as in Equation 3 \[13\]:

$$\bar{e}_x_{ch,k} = \sum_k x_k \bar{e}_{x_{ch}}^k + \sum_k x_k R_0 \ln x_k \tag{3}$$

Finally, the kinetic exergy is normally defined by Equation 4:

$$\bar{e}_x_{ke,k} = m_a \frac{V_{aircraft}^2}{2} \tag{4}$$

Some other exergy-based measures are also useful for the system evaluation, which include the exergy efficiency, exergy destruction rate, relative exergy destruction, fuel depletion ratio productivity lack, fuel and product exergy factors, and the rate of exergetic improvement potential. They are described as follow:

- Exergy efficiency of each component is the ratio of the product exergy to the fuel exergy, as given by Equation 5:

$$\varepsilon_k = \frac{\dot{P}_k}{\dot{F}_k} \tag{5}$$

- Exergy destruction rate is the rate of exergy destruction due to losses within the components and it is calculated by Equation 6:

$$\dot{E}_{x_{des,k}} = \dot{F}_k - \dot{P}_k \tag{6}$$

- Relative exergy destruction gives the exergy destruction of each component as a ratio of the total exergy destruction. This value is normalised and hence permits comparison of performance among different components of the system. It is given in Equation 7:

$$X_k = \frac{\dot{E}_{x_{des,k}}}{\dot{E}_{x_{des,tot}}} \tag{7}$$

- Fuel depletion ratio and productivity lack describe the exergy destruction for each component as a percentage of the total fuel and product exergy, respectively, given by Equation 8(a) and Equation 8(b).

$$\delta_k = \frac{\dot{E}_{x_{des,k}}}{\dot{F}_{tot}} \tag{8a}$$

$$\xi_k = \frac{\dot{E}_{x_{des,k}}}{\dot{P}_{tot}} \tag{8b}$$
• Fuel and product exergy factors estimate the parts of the fuel and product exergy for a system unit as fraction of the total fuel and product exergy values, respectively. They can be calculated using Equation 9(a) and Equation 9(b).

\[
f_k = \frac{F_k}{F_{tot}} \quad (9a)
\]

\[
p_k = \frac{P_k}{P_{tot}} \quad (9b)
\]

• Rate of exergetic improvement potential defines the percentage of potential improvement for each component. It helps to define the component that has to be improved. This can be calculated using Equation 10.

\[
IP_k = (1 - \varepsilon_k)(\dot{F}_k - P_k) \quad (10)
\]

The main component of the turbofan engine that will be reviewed in this study is the exhaust, which is different from other previous studies. The exergy inlet, outlet and efficiency equations for the exhaust are given by Equation 11(a), Equation 11(b) and Equation 11(c), respectively.

\[
E_{x_{in,exh}} = E_{x_{ph,exh}} + E_{x_{ch,exh}} \quad (11a)
\]

\[
E_{x_{out,exh}} = E_{x_{ke,exh}} \quad (11b)
\]

\[
\varepsilon_{exh} = \frac{E_{x_{out,exh}}}{E_{x_{in,exh}}} \quad (11c)
\]

4. Exergetic Sustainability Assessment for Turbofan Engine

The computed exergetic parameter is then used to deduce the exergy-based sustainability parameters. This study considers take-off condition at sea level. To calculate the exergy efficiency of the overall turbofan engine, the useful product of the engine (i.e. thrust power) and the resources needed (i.e fuel and inlet air chemical exergy) have to be defined. Thrust for a mixed flow and un-chocked turbofan engine is calculated using Equation 12, where \( m_{exh} \) and \( V_{exh} \) are the mass flow rate and aircraft velocity at the exhaust, respectively, \( f \) is the ratio of mass flow rate of the fuel to the total mass flow of rate of air, \( \beta \) is the bypass ratio and \( V_0 \) is the aircraft velocity at intake fan.

\[
T = m_{exh} \{(1 + f + \beta)V_{exh} - (1 + \beta)V_0\} \quad (12)
\]

Thrust power and exergy efficiency are derived using Equation 13 and Equation 14, respectively.

\[
\dot{T} = TxV_0 \quad (13)
\]

\[
\varepsilon = \frac{T}{\dot{F}_{tot}} \quad (14)
\]

Several exergy-based sustainability parameters are evaluated for a turbofan engine based on Ref. [14]. First, the waste exergy ratio is the ratio of total waste exergy output to total exergy input, as given in Equation 15. In a turbofan engine studied, all waste exergy is unused as the exhaust emissions cannot be recovered.

\[
Waste exergy ratio = \frac{\dot{F}_{tot} - \dot{T}}{\dot{F}_{tot}} \quad (15)
\]

Next, recoverable exergy amount given by Equation 16 is null in this case study due to unrecoverable exhaust emissions to the atmosphere.

\[
l_{re} = \frac{\text{Recoverable exergy}}{\dot{F}_{tot}} \quad (16)
\]
Furthermore, the exergy destruction factor indicates the reduction in the positive effect of the engine based on exergy sustainability. It is defined as the ratio of total exergy destruction to total fuel exergy, which is given by Equation 17.

$$f_{exd} = \frac{E_{x,dest,\text{tot}}}{E_{\text{tot}}'}$$  \hspace{1cm} (17)

Meanwhile, the environmental effect factor is defined as in Equation 18.

$$r_{eef} = \frac{\text{Waste exergy ratio}}{\varepsilon}$$  \hspace{1cm} (18)

Finally, the sustainability assessment of a turbofan engine through exergy method can be addressed by applying the exergetic sustainability index. It is the inverse of the environmental effect factor, as given by Equation 19, and varies from 0 to 1.

$$\Theta_{esi} = \frac{1}{r_{eef}}$$  \hspace{1cm} (19)

5. Results and Discussion

In this study, the exergy efficiency, exergy destruction, fuel depletion ratio, productivity lack, fuel and product exergy factors, and the improvement potential rate of each component of CF6 turbofan engine are defined and evaluated using sea level data. This type of engine has been used in multiple aircraft including Airbus A300/310/330 and Boeing B767/747. It has a relatively high by-pass ratio at around 4.5. The data used in this analysis such as mass flow rate, molar specific enthalpy and entropy are all tabulated in Table 1 [15], along with the results obtained for the exergy rates of different points in the turbofan engine. The obtained results are compared to the previous study in Ref. [6], which concerns a turbofan engine with separated exhaust.

Table 1: Thermodynamics parameters for the turbofan engine

| Component             | Mass flow rate (kg/s) | Molar specific enthalpy (kJ/kmol) | Molar specific entropy (kJ/kmol.K) | Physical exergy rate (MW) | Chemical exergy rate (MW) | Kinetic exergy rate (MW) | Total exergy rate (MW) |
|-----------------------|-----------------------|-----------------------------------|-----------------------------------|--------------------------|--------------------------|--------------------------|-------------------------|
| Fan inlet             | 679.18                | 8939.63                           | 200.04                            | 0.00                     | -1.28                    | -                        | -1.28                   |
| Fan outlet            | 679.18                | 10508.52                          | 200.34                            | 34.60                    | -1.28                    | -                        | 33.32                   |
| LPC inlet             | 119.54                | 10508.52                          | 200.34                            | 6.09                     | -0.23                    | -                        | 5.86                    |
| LPC outlet            | 119.54                | 11557.58                          | 200.91                            | 9.70                     | -0.23                    | -                        | 9.47                    |
| HPC inlet             | 119.54                | 11557.58                          | 200.91                            | 9.70                     | -0.23                    | -                        | 9.47                    |
| HPC outlet            | 116.14                | 25805.49                          | 203.13                            | 63.78                    | -0.22                    | -                        | 63.56                   |
| CC inlet              | 112.74                | 25805.49                          | 203.13                            | 61.92                    | -0.21                    | -                        | 61.71                   |
| CC outlet             | 114.94                | 49321.70                          | 225.56                            | 129.12                   | 0.28                     | -                        | 129.40                  |
| HPT inlet             | 114.94                | 49321.70                          | 225.56                            | 129.12                   | 0.28                     | -                        | 129.40                  |
| HPT outlet            | 121.74                | 33864.62                          | 226.02                            | 71.24                    | 0.30                     | -                        | 71.54                   |
| LPT inlet             | 121.74                | 33864.62                          | 226.02                            | 71.24                    | 0.30                     | -                        | 71.54                   |
| LPT outlet            | 121.74                | 24013.09                          | 227.05                            | 28.54                    | 0.30                     | -                        | 28.84                   |
| Mixed exhaust inlet   | 681.38                | -                                 | -                                 | 85.92                    | 1.67                     | -                        | 87.59                   |
| Mixed exhaust outlet  | 681.38                | -                                 | -                                 | -                       | -                        | 26.83                    | 26.83                   |
| Bleed air 1           | 3.40                  | 21036.40                          | 203.70                            | 1.29                     | -0.01                    | -                        | 1.28                    |
| Bleed air 2           | 3.40                  | 25805.49                          | 203.15                            | 1.86                     | -0.01                    | -                        | 1.86                    |
| Fuel                  | 2.20                  | 7253.00                           | -                                 | -                       | 100.97                   | -                        | 100.97                  |
Figure 2 and Figure 3 show that the turbine has the greatest exergy efficiency while the exhaust is found to have the lowest one. The high efficiency in the fan, compressors and turbines are due to their high isentropic efficiencies, which is around 80-95%. This implies that the highest exergy loss for the system would be from the exhaust, followed by the combustion chamber. The loss of exergy from the exhaust is believed to be caused by high-quality energy that is discharged from the component. In the meantime, the loss in combustion chamber can be contributed to the internal irreversibility within the component. From both figures, it is also observed that all turbomachinery components exhibit a high value of exergy efficiency except for LPC. This is understandable since LPC is used to avoid irregular flow, stall and blocking, and to achieve high-pressure ratio that subsequently leads to irreversibilities. Because of this, some parts of the compressor are required to operate at rather low rotation per minute (RPM). Comparing these results to the those with separated exhaust in Ref. [6], exergy efficiencies for fan and core engine exhaust are found to be around 12%, which are much lower than the those for a mixed exhaust engine studied in this paper. Consequently, the total exergy loss in fan and core engine exhaust is higher than the that in the mixed exhaust alone.

In Figure 4, exhaust has the largest fuel depletion ratio and productivity lack with values of 9.97% and 12.39%, respectively. It is followed by the combustion chamber at 7.29% and 9.06%, respectively, where chemical energy is converted to heat. Comparing with the exergy analysis for turbofan engine with separate exhaust in Ref. [6], the fuel depletion ratio and productivity lack of the mixed exhaust engine are higher. This might be due to additional heating of the secondary air exiting the fan by the primary air from core engine when they are mixed to attain the same temperature before exiting the exhaust. Furthermore, fuel and product exergy factors in Figure 5 indicate that combustion chamber is the primary consumer of the total fuel and product exergy with 35.65% and 36.77%, respectively. It is followed by HPT with 29.04% and 37.05%, respectively. These results are anticipated since both the conversion of chemical energy to heat and the conversion of mechanical to electrical power occur within these two components. Meanwhile, it is good to acknowledge that the sum of fuel and product exergy factors of both fan and core engine exhaust when they are in separated exhaust as reported in Ref. [6] is lower than those in the mixed exhaust.

Figure 6 highlights that more than 50% of the total exergy destruction rate occurs in the exhaust. Nevertheless, this value is found to be lower than the total relative exergy destruction in fan and core engine exhaust separately found in the previous study, which is 66% [6]. This is totally expected since the exergy loss rate of both components separately is higher than the loss in mixed exhaust alone. The results of potential improvement rate in Figure 7 implies that the mixed exhaust and the combustion chamber still deserve more focus and research than the other components. Although recent advances in combustion have been initiated, it is still restricted to the laws of thermodynamics.

Lastly, the most significant contribution of this study is the exergetic sustainability performance for the engine, which is shown in Figure 8. This part of the study has never been done for a CF6 engine.
In Figure 8, the obtained result for waste exergy ratio is slightly higher than theoretically suggested (approximately 70%) and this implies that significant amount of provided exergy rate to the system is wasted. Subsequently, the exergetic sustainability indicator for the mixed exhaust engine is rather low, which is 0.37. Meanwhile, the higher the value of the sustainability index, the better it is for practical
applications. The other notable factor is the exergy destruction factor, which is calculated to be 0.39. The amount of recoverable exergy is zero because the emissions released cannot be recovered in the engine. To improve the environmental sustainability, it is necessary not only to utilize sustainable or renewable energy sources, but also to use the natural sources more efficiently while minimizing the environmental damage.

6. Conclusion
In this paper, exergy analysis and sustainability assessment based on exergy for a turbofan engine with mixed exhaust during take-off condition at sea level have been performed. This study aims to present the possibilities and advantages that the turbofan engine with mixed exhaust and sustainability exergy-based study might offer to the aircraft propulsion system. The main conclusions that can be outlined from this study are as follows:

- The exergy efficiency for the mixed exhaust component is calculated to be higher (48.1%) than the one for fan and core engine separately (12.94% and 12.71%, respectively).
- The overall exergy efficiency for turbofan engine with mixed exhaust is 26.9%.
- The other important parameter that shows a drop in positive effect is the exergy destruction factor, which is found to be 0.39.

Sustainability index based on exergy analysis has been shown to be an important method to assess the sustainability of the turbofan engine. Exergy aids in the determination of improvement potential rates and reduction in the irreversibility of the process. In the future, it is advisable to perform an exergo-environmental analysis and life-cycle assessment to this turbofan engine to assess the environmental impact of the engine.

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