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Exergy-based sustainability analysis of a low-bypass turbofan engine: A case study for JT8D

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Abstract

The growth in demand for air transport is a problem for the global and local environment. There are, moreover, fundamental conflicts with sustainable development objectives. Sustainability demands a sustainable supply of energy without causing negative environmental impacts of aircrafts and its engines. In this paper, an investigation of exergo-sustainability indicators is reported for a low bypass (0.96 to 1) turbofan engine with 72 kN thrust force. Six selected exergetic indicators are selected for the analysis. The study is based on three approaches: energy, exergy and sustainability. In this regard, considering thermodynamics laws and Brayton cycle equations, the exergy efficiency of the engine is 11 % having waste exergy ratio of 0.348. In addition, exergetic sustainability index of the low bypass turbofan engine is found to be 0.316, while environmental effect factor is calculated to be 3.163. On the other hand, the recoverable exergy amount of the engine is zero since the emissions released from fan bypass duct and core engine exhaust cannot be recoverable in the engine.

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Keywords: sustainability; low bypass turbofan engine; exergy; energy

1. Introduction

Continued development of aircraft propulsion systems has resulted in bypass engines. These moderately bypass ratio engines have evolved through technological improvements in turbine inlet temperatures, overall pressure ratios,

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specific thrust, and propulsive, thermal and overall efficiencies. Bypass engines provide lower specific fuel consumption, short takeoff distances, faster climb out and lower community noise. Fuel efficiency of aircraft has in recent years risen in prominence as a design consideration in the establishment of turbofan engine technology. It is based on the reduction of weight and improvement of aircraft engine efficiency. Greenhouse gas (GHG) emissions from the environmentally benign turbofan engines could be lowered by reducing activity, energy efficiency optimization and sustainability of the engines. For this purpose, the scientists, researchers, and engineers aim at optimizing the energy saving and consumption, and thus, develop the turbofans [1–6].

In terms of the second-law of thermodynamics, minimizing irreversibilities in turbofan engines becomes a significant challenge for better sustainability. On the other hand, turbofan engine technology has a vital role to play in mitigating the environmental impacts of air vehicles. The exergy of an emission to the environment, therefore, is a measure of the potential of the emission to change or impact the environment. At this point of view, exergy efficiency is also a useful tool for evaluating aircraft environmental and sustainability performance [7–19].

A detailed literature review has been performed on thrust modeling, energy, exergy, environment, economy and sustainability analyses for various aero-gas turbine engines [20–34]. In the literature, various exergo-sustainability analyses of aircraft engines have been reported [28, 30–32]. Recently some studies [34, 36] on the energetic and exergetic performance analyses of a low bypass turbofan engine have appeared. The general objective of this paper is to calculate the sustainability indices of the JT8D low bypass turbofan engine. Through a literature review, lack of exergo-sustainability analysis of the JT8D low bypass engine emphasizing the originality of this article is the main motivation.

Nomenclature

c_p	Specific heat (kJ/(kg K))
E	Energy rate (MW)
ex	Specific exergy (kJ/kg)
Ex	Exergy rate (MW)
f	Factor
F	Fuel exergy (MW)
g	Gibb's free energy (kJ/kmol)
h	Specific enthalpy (kJ/kg)
IP	Exergetic improvement potential rate (MW)
LHV	Lower Heating Value of fuel (kJ/kg)
m	Mass flow rate (kg/s)
p	Product exergy factor
P	Pressure (kPa); product exergy (MW)
Q	Heat (kJ)
R	Specific gas constant (kJ/kg K)
r	Ratio for waste exergy, recoverable exergy, environmental effect factor
ρ	Density (kg/m^3)
s	Specific entropy (kJ/(kg K))
T	Temperature (K)
u	Velocity of stream (m/s)
U	Specific intermolecular energy (J/kg)
v	Specific volume (m^3/kg)
X	Relative exergy destruction
x	Chemical component
W	Work rate (MW)
y_i	Mole fraction of component i in the exhaust gas
y_i^e	Mole fraction of component i in the environment
δ	Fuel depletion ratio
ξ	Productivity lack

Θ	Index for exergetic sustainability
χ	Relative irreversibility
η	Efficiency
Ψ	Flow exergy (kJ/kg)

Indices

a	Air
c	Compressor
cc	Combustion chamber
ch	Chemical
dest	Destroyed, destruction
e	Exit
eef	Environmental effect
esi	Exergetic sustainability
ex	Exergy
exd	Exergy destruction
f	Fuel
LPC	Low pressure compressor
HPC	High pressure compressor
LPT	Low pressure turbine
HPT	High pressure turbine
i	Successive number of elements
in	Inlet
k	Location
kn	Kinetic
o	Overall (for first law efficiency)
out	Outlet
per	Perfect
ph	Physical
pt	Potential
re	Recoverable
t	Total
wex	Waste exergy
u	Useful
0,1, 2..	Ambient conditions, reference environment and station numbering

2. System Description

The JT8D turbofan engine family shown in Fig. 1, includes the thrust range from 62 to 77 kN and power 727, 737-100/200, and DC-9 aircraft. More than 14,000 JT8D engines have been produced, totalling more than one-half billion hours of service with more than 350 operators making it the most popular of all low-bypass turbofan engines ever produced. The engine is an axial-flow front turbofan engine incorporating dual-spool design. There are two coaxially-mounted independent rotating assemblies: one rotating assembly for the low pressure compressor (LPC) which consists of the first six stages (i.e. six pairs of rotating and stator blades, including the first two stages which are for the bypass turbofan), driven by the second three-stage turbine; and a second rotating assembly for the high-pressure seven-stage compressor (HPC) section. The HPC is driven by the first single stage turbine. The front-mounted bypass fan has two stages. The annular discharge duct for the bypass fan runs along the full length of the engine, so that both the fan air and exhaust gases can exit through the same nozzle [36]. JT8D engine energy and exergy parameters are listed in Table 1 according to station temperature, pressure and mass flow.

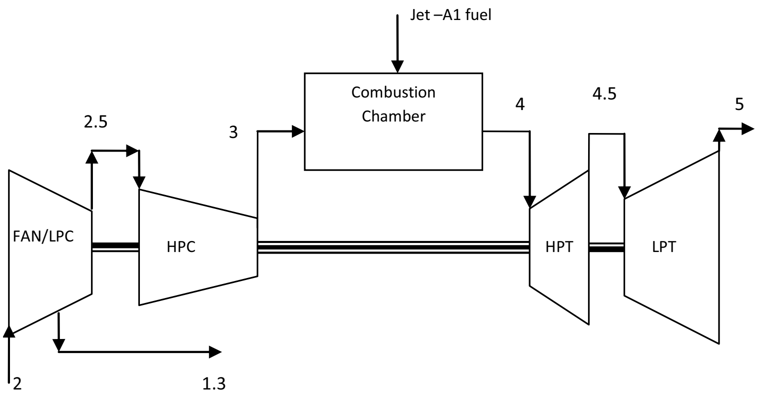

Fig. 1. Schematic illustration of the low bypass turbofan engine.

Table 1. Low bypass turbofan engine parameters.

Station No	Location	Mass flow (kg/s)	Temperature (K)	Pressure (kPa)	Energy flow (MW)	Exergy flow (MW)
0	Air	142.7	288.15	101.35	0	0
2	Fan/LPC inlet	142.7	288.15	101.35	0	0
1.3	Fan bypass outlet	74.74	361	193	5.60	4.58
2.5	Fan/LPC core outlet	67.95	453	413.6	11.77	10.3
2.5	HPC inlet	67.95	453	413.6	11.77	10.3
3	HPC outlet	67.95	700	1,606.5	31.42	26.92
3	Combustor inlet	67.95	700	1,606.5	31.42	26.92
3	Fuel	1.050	288.15	2,000	44.94	46.96
4	Combustor outlet	69	1211	1,517	73.76	55.01
4	HPT inlet	69	1211	1,517	73.76	55.01
4.5	HPT outlet	69	967	567	52.95	34.8
4.5	LPT inlet	69	967	567	52.95	34.8

Note: Some parameters are modified and calculated from [34–36].

3. Exergo-Sustainability Methodology Application for the Low Bypass Turbofan Engine

The hot gases leave the engine at very high speeds that produce the thrust which is expressed as following:

$$\dot{F} = \dot{m}(V_{out} - V_{in}) + A_{out}(P_{out} - P_{in}) \tag{1}$$

where
ṁ mass flow rate;
V velocity;
A exhaust area;
P pressure.

Assuming that the engine is run on the ground, the inlet air speed and net thrust force is assumed to be 72 m/s and 72 kN. Moreover, the second term can be negligible since the changes between inlet pressure and outlet pressure are very little.

$$\dot{E}x_u = (Net\ thrust).(True\ Air\ Speed) = \tau.u = (72{,}000)(72) = 5.18MW \tag{2}$$

The useful exergy ($\dot{E}x_u^{JT8D}$) of the engine or the specified take off running parameters has been calculated as 5.18 MW. In this paper the exergy-based parameters for the low bypass turbofan engine is studied to seek how some of their operating aspects and system characteristics affect the sustainability. The exergetic sustainability indicators are exergy efficiency, waste exergy ratio, recoverable exergy rate, exergy destruction factor, environmental effect factor and exergetic sustainability index [31, 33, 34, 36]. These parameters are expected to quantify how the low bypass turbofan engine becomes more environmentally benign and sustainable. The calculation of exergetic sustainability indicators are explained below.

The general exergy balance is expressed as following:

(Total exergy input)=(Total useful exergy output)+(Total waste exergy output) + (Total exergy destruction) (3a)

$$\sum \dot{E}x_{t,in} = \sum \dot{E}x_{u,out} + \sum \dot{E}x_{w,out} + \sum \dot{E}x_{dest,out} \tag{3b}$$

Total inlet exergy $\dot{E}x_{t,in}$ is equal to chemical exergy of fuel burned in combustor. Useful exergy is calculated as 5.18 MW. For 1.05 kg/s fuel flow the fuel chemical exergy is obtained as 46.96 MW. For 1.05 kg/s fuel flow,

$$\dot{E}x_{t,in}^{JT8D} = \dot{E}x_{fuel,ch}^{JT8D} = 46.96MW \tag{4}$$

Total destructed exergy ($E_{dest,out}$) can be calculated by the sum of destructed exergy of the engine components from Table 1.

$$\dot{E}x_{d,out}^{JT8D} = 25.41MW \tag{5}$$

The waste exergy ($\dot{E}x_{w,out}^{JT8D}$) can be found by Eq. (6) as below:

$$\dot{E}x_{w,out}^{JT8D} = \dot{E}x_{t,in}^{JT8D} - \dot{E}x_{u,out}^{JT8D} - \dot{E}x_{dest}^{JT8D} = 46.96 - 5.18 - 25.41 = 16.37MW \tag{6}$$

Exergy efficiency (η_{ex}) is calculated by ratio of useful exergy to inlet exergy [27, 29, 30, 34, 35]. From this expression the exergetic efficiency of the JT8D is calculated as following:

$$\eta_{ex}^{JT8D} = \frac{\dot{E}x_{u,out}^{JT8D}}{\dot{E}x_{t,in}^{JT8D}} = \frac{5.18}{46.96} = 0.11 \tag{7}$$

The low bypass turbofan engine's aim is to produce the thrust which is obtained by the momentum of the burned gases in order to fly the aircraft. During engine operation hot exhaust gases are discharged into the environment. Waste exergy value of the engine studied here is calculated as 16.37 MW. Waste exergy ratio (r_{we}) can be calculated by ratio of total waste exergy to the total inlet exergy [30, 32, 36].

Waste exergy ratio = (Total waste exergy out) / (Total exergy inlet) (8)

As written in algebraic form:

$$r_{we} = \frac{\sum \dot{E}x_{w,out}}{\sum \dot{E}x_{in}} \tag{9}$$

Waste exergy ratio (r_{we}^{JT8D}) of JT8D

$$r_{we}^{JT8D} = \frac{\sum \dot{E}x_{w,out}^{JT8D}}{\sum \dot{E}x_{t,in}^{JT8D}} = \frac{16.37}{46.96} = 0.348 \tag{10}$$

Recoverable exergy ratio (r_{re}) is calculated by ratio of recoverable exergy to inlet exergy value. The destructed and loss exergies of aircraft turbofan engine cannot recoverable so recoverable exergy and exergy ratio values are zero for the JT8D.

Recoverable exergy ratio = Recoverable exergy / Total exergy inlet (11)

$$r_{re}^{JT8D} = \frac{\sum \dot{E}x_{re,o}^{JT8D}}{\sum \dot{E}x_{t,in}^{JT8D}} = \frac{0}{46.96} = 0 \tag{12}$$

Exergy destruction factor (r_{exd}) is a significant parameter indicating the decrease of the positive effect of the engine on exergy-based sustainability. Exergy destruction factor can be calculated by the ratio of exergy destruction to the total exergy input [28, 30, 33]. Exergy destruction factor of the JT8D is described as follows:

Exergy destruction factor =Exergy destruction/Total exergy input (13)

This can be written as in algebraic form,

$$f_{exd} = \frac{\dot{E}x_{dest}}{\dot{E}x_{in}} \text{ (Ranging from 0 to 1)} \tag{14}$$

For JT8D at maximum net thrust power:

$$f_{exd}^{JT8D} = \frac{\dot{E}x_{dest}^{JT8D}}{\dot{E}x_{t,in}^{JT8Dl}} = \frac{25.41}{46.96} = 0.541 \tag{15}$$

Another important sustainability indicator to be reviewed is environmental effect factor (r_{eef}) which is calculated the ratio of waste exergy ratio to the exergy efficiency.

Environmental effect factor= Waste exergy ratio /(Exergy efficiency) (16)

as

$$r_{eef} = \frac{r_{we}}{\eta_{ex}} \tag{17}$$

For the JT8D engine:

$$r_{eef}^{JT8D} = \frac{r_{we}^{JT8D}}{\eta_{ex}^{JT8D}} = \frac{0.348}{0.11} = 3.163 \tag{18}$$

Exergetic sustainability index (Θ_{esi}) is a vital parameter among exergetic sustainability indicators to assess the system's sustainability level. Its function of environmental effect factor can be determined by ratio of 1 to the environmental effect factor. The range of this index is between 0 and ∞ [30, 32, 35]. The higher efficiency means low waste exergy ratio and low environmental effect factor as a result higher exergetic sustainability index.

Exergetic sustainability index = 1 / Environmental effect factor (19)

$$\Theta_{esi} = \frac{1}{r_{eef}} \tag{20}$$

For the JT8D engine:

$$\Theta_{esi}^{JT8D} = \frac{1}{r_{eef}^{JT8D}} = \frac{1}{3.163} = 0.316 \tag{21}$$

In Fig. 2, all exergetic sustainability parameters of the engine are summarized.

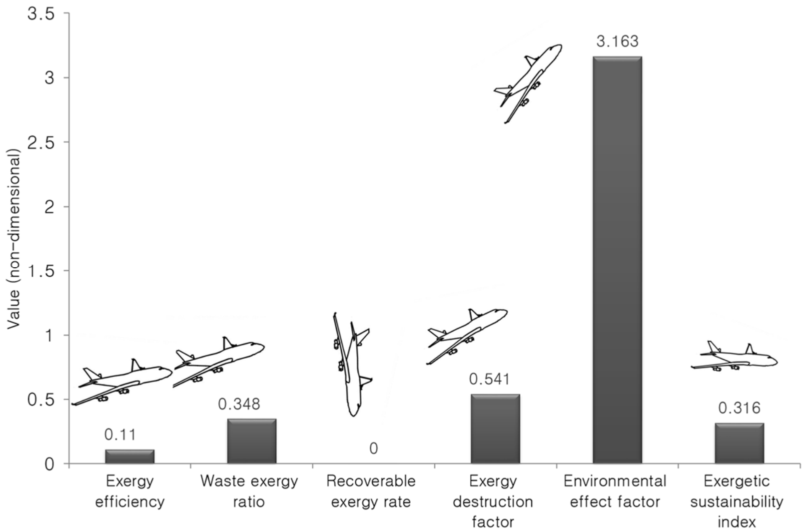

Fig. 2. Sustainability exergetic labels of the low bypass turbofan engine.

4. Conclusion

This study describes a methodology aimed at an assessment of sustainability analysis for a given low bypass aircraft gas turbine engine. The second law of thermodynamics involves the reversibility or irreversibility of processes and is a very important aspect in the exergy method of aircraft engine analysis. From the viewpoints of thermodynamic sustainability, turbofan engine systems can be considered as one of sustainable energies for aircrafts. This study is to calculate the sustainability for a low bypass turbofan engine. In fact, air transportation brings significant sustainability-related benefits. Aircraft turbofans can therefore be viewed as making a positive contribution to sustainability impacts. It is true that aviation also incurs sustainability costs such as finite resource depletion, noise, atmospheric emissions which contribute to reduce local air quality and climate change, water and land pollution, and various associated adverse health impacts. For a future work, environmental and economic analysis can be recommended for the JT8D engine and similar aircraft power systems.

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