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Research Paper

Exergy modeling for evaluating sustainability level of a high by-pass turbofan engine used on commercial aircrafts

Ozgur Balli

First Air Supply and Maintenance Center, TurAF, Eskisehir, Turkey

HIGHLIGHTS

- Presenting an exergy based sustainability analyzing methodology.
- Thirteen sustainability metrics are used to evaluate sustainability level of a high by-pass turbofan engine.
- Analyzing sustainability performance of engine for the Maximum Take-Off mode and the Take-Off Running Power mode.
- Comparing the sustainability indicator values of turbofan engine for operation modes.

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ABSTRACT

This study presents an exergy modeling to evaluate the sustainability level of a high by-pass turbofan engine used on commercial aircrafts. The nineteen sustainability indicators for the component level and the thirteen sustainability metrics for the system level are recommended based on the exergy analysis. The PW4056 model turbofan engine is examined by the suggested sustainability metrics for the Maximum Take-Off Power (MTOP) operation mode and the Take-Off Running Power (TORP) at the seal level. As a result of the sustainability analysis, The exergy efficiency, improved exergy efficiency, waste exergy ratio, fuel exergy waste ratio, improvable exergy potential ratio, waste exergy improvement potential ratio, fuel exergy improvement potential ratio, productivity lack ratio, environmental effect factor, ecological effect factor, exergetic sustainability index, sustainable efficiency factor and waste exergy cost rate are estimated to be 0.268, 0.577, 0.732, 0.781 0.536, 0.732, 0.572, 2.730, 2.730, 3.495, 0.366, 1.366, 0.018 kW/$ for the MTOP operation modes while they are obtained to 0.205, 0.557, 0.795, 0.848, 0.631, 0.795, 0.674, 3.869, 4563, 0.258, 1.258, 0.019 kW/$ for the TORP operation modes. Comparing the sustainability indicator values of MTOP mode to the sustainability indicator values of the TORP mode, the engine operates the better sustainability level at the MTOP operation mode.

1. Introduction

Aviation sector brings significant benefits, both directly through the jobs it creates and indirectly through the facilitation of global trade and tourism. However, its activities also contribute to climate change, noise and local air quality impacts, and consequently affect the health and quality of life of public. The main aircraft engine emission pollutants are carbon dioxide (CO_2), nitrogen oxides (NO_x), sulphur oxides (SO_x), unburned hydrocarbons (UHC), carbon monoxide (CO), particulate matter (PM) and soot. Aircraft CO_2 emissions had increased from 88 to 156 million tons (+77%) between 1990 and 2005 while it had increased by 5% between 2005 and 2014. The increase in emissions was however less than the increase in passenger kilometers flown over the same period (2005–2014). This was due to an improvement in fuel efficiency driven by the introduction of new aircraft, removal of older aircraft, and improvements in operational practice. The average fuel burn per passenger kilometer flown for passenger aircraft, excluding business aviation, went down by 19% over this same period. However, projections indicate that future technology improvements are unlikely to balance the effect of future traffic growth. Under the base traffic forecast and advanced technology improvement rate, it is estimated that CO_2 emissions increase by 44% from 144 Mt in 2005 to 207 Mt in 2035. On the other hand, while NO_x emissions increased significantly from 316 to 585 thousand tons (+85%) between 1990 and 2005, they increased +13% between 2005 and 2014. Under the base air traffic forecast and assuming an advanced NO_x technology improvement rate, emissions will reach around 920 thousand tons in 2035 (+42% compared to 2005). Emissions

E-mail address: balli07balli@yahoo.com

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Nomenclature

A	area (m^2)
CC	combustion chamber
c_P	specific heat capacity (kJ/kg·K)
$CIExIPR$	component inlet exergy improvement potential ratio (%)
$\dot{E}$	energy rate (kW)
$EcoEF$	ecological effect factor (–)
ED	exhaust duct
EEF	environmental effect factor (–)
ET	engine thrust (kN)
$\dot{E}x$	exergy rate (kW)
$\dot{E}xIP$	exergy improvement potential rate (kW)
$ExDCR$	exergy destruction cost rate (kW/$)
$ExDIR$	exergy destruction improvement ratio (%)
$ExSI$	exergetic sustainability index (–)
FAN	fan
FD	fan duct
$FExDR$	fuel exergy depletion ratio (%)
$FExIPR$	fuel exergy improvement potential ratio (%)
$FExWR$	fuel exergy waste ratio (–)
FRI	fuel ratio indicator (%)
HPC	high pressure compressor
HPT	high pressure turbine
$HPTMS$	high pressure turbine mechanical shaft
$IExDR$	Inlet exergy depletion ratio (%)
LHV	lower heating value of fuel (kJ/kg)
LPC	low pressure compressor
LPT	low pressure turbine
$LPTMS$	low pressure turbine mechanical shaft
$\dot{m}$	mass flow rate (kg/s)
$MTOP$	maximum take-off power mode
MIL	military operation mode
P	pressure (kPa)
PLR	Productivity lack ratio (%)
PRI	Product ratio indicator (%)
R	universal gas constant (kJ/kg K)
$RExDR$	relative exergy destruction ratio (%)
$RExDCR$	relative exergy destruction cost rate (%)
$RExIPR$	relative exergetic improvement potential ratio (%)
SEF	sustainable efficiency factor (–)
T	temperature (K)
TFE	turbofan engine
$TORP$	take-off runway power mode
V	velocity (m/s)
$\dot{W}$	work rate (kW)
$WExCR$	waste exergy cost rate (kW/$)
$WExR$	waste exery ratio (–)
$WExIPR$	waste exergy improvement potentioal ratio (–)

Greek letters

ε	specific exergy (kJ/kg)
ρ	air density (kg/m^3)
ξ	fuel exergy grade function
ψ	exergetic efficiency (%)
Ψ	improved exergetic efficiency (%)

Subscripts

a	air
CC	combustion chamber
D	destruction
ED	exhaust duct
F	inlet streams as a fuel
FAN	fan
FD	fan duct
g	combustion gas
HPC	high pressure compressor
HPT	high pressure turbine
$HPTMS$	high pressure turbine mechanical shaft
in	input
k	the k'th component
KN	kinetic
L	losses
LPC	low pressure compressor
LPT	low pressure turbine
$LPTMS$	low pressure turbine mechanical shaft
out	output
P	pressure
Pr	product
T	temperature
TFE	turbofan engine
tot	total
WE	waste exergy
0	dead state conditions

Superscripts

CH	chemical
KN	kinetic
PH	physical
PT	potential

of HC, CO and on volatile PM had decreased between 2005 and 2014, while full flight emissions of volatile PM increased by 7%. However, the total emissions of each of these pollutants are forecast to increase over the next twenty years [1].

Fuel efficiency of aircraft and helicopter becomes greater concern in recent years caused by rising fuel costs and as well as environmental impact of aviation emissions [2]. A reduction of energy use will also reduce gaseous emissions and related to the conservation of the environment [3].

Dincer and Rosen [4] stated the relationships between energy and exergy, exergy and the environment, energy and sustainable development, and energy policy making and exergy in detail. Exergy is a powerful tool for understanding and improving the sustainability of processes and systems. However, exergy analysis is a powerful technique that can assess and improve the efficiency of a process, device or system, and enhance its environmental and economic performance [5].

A system with lower waste exergy rate has more useful exergy and subsequently more potential to do work. A less efficient system has more waste exergy rate because of exergy destruction and losses and subsequently less potential to do work. Generally, total waste exergy rate can be reduced by minimizing waste and losses in natural resources and physical resources, which ultimately moves society towards more sustainable development. In addition to measuring the consumed exergy, exergetic sustainability indicators measure the sustainability performance of a system. Developing a more sustainable strategy such as improving labor payments and benefits, paying more attention to environmental remediation, making donations for societal improvement, etc. can preserve the exergetic contents of human work, capital, energy and material, and provide enhanced environmental remediation, all of which lead to more sustainable development. Exergetic sustainability indicators can be used to measure the level of sustainability. Decision makers and owners in production systems can