Energy 93 (2015) 716–729

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Exergy analysis of a turbofan engine for an unmanned aerial vehicle during a surveillance mission

Yasin Şöhret [a,*], Ali Dinç [b], T. Hikmet Karakoç [c]

[a] Graduate School of Sciences, Anadolu University, TR-26470, Eskişehir, Turkey
[b] Tusas Engine Industries Inc., TR-26003, Eskişehir, Turkey
[c] Faculty of Aeronautics and Astronautics, Anadolu University, TR-26470, Eskişehir, Turkey

ARTICLE INFO

Article history:
Received 8 June 2015
Received in revised form
8 September 2015
Accepted 17 September 2015
Available online 22 October 2015

Keywords:
Aircraft engine
Cycle analysis
Gas turbine
Exergy analysis
Turbofan
UAV

ABSTRACT

In this study, an exergy analysis of a turbofan engine, being the main power unit of an UAV (unmanned aerial vehicle) over the course of a surveillance mission flight, is presented. In this framework, an engine model is firstly developed, based upon engine design parameters and conditions using a genuine code. Next, the exergy analysis is performed according to thermodynamic laws. At the end of the study, the combustion chamber is identified as the most irreversible component of the engine, while the high pressure turbine and compressor are identified as the most efficient components throughout the flight. The minimum exergy efficiency is 58.24% for the combustion chamber at the end of the ingress flight phase, while the maximum exergy efficiency is found to be 99.09% for the high pressure turbine at the start of the ingress flight phase and landing loiter. The highest exergy destruction within the engine occurs at landing loiter, take-off and start of climb, with rates of 16998.768 kW, 16820.317 kW and 16564.378 kW respectively.

1. Introduction

As a result of technological development and rapid advances in engineering sciences and industry, world energy demand in the 21st century is ever increasing. Recent reports by well-regarded institutions [1,2] reveal that fossil fuels are still the most common energy resources, rather than renewable energy resources. Therefore, there is pressure to develop more efficient energy system designs, and to utilize and sustain energy more efficiently. At this point, thermal engineering, commonly referred to energy engineering, plays a vital role. Exergy in particular, is a prominent tool in this field of engineering providing benefits, such as the evaluation and optimization of energy systems. Exergy analysis comprises the first and second laws of thermodynamics. The first law deals with energy conservation and forms changes of energy within the system. Thus, it enables us to understand the conversion rate of energy into another form, while the second law of thermodynamics explains the theoretical limitations of a system under actual operating conditions. Exergy analysis, which benefits from both the first and second laws of thermodynamics, pays attention to the quality of energy consumption and conversion within a system in addition to the quantity. Therefore, it leads us to understand the irreversibility and loss within the examined system [3–5]. For this purpose, many studies have been presented in the literature for the evaluation of various energy systems e.g. power plants, engines, heating and cooling systems and suchlike [6–15].

The transportation sector accounts for approximately 25% of energy consumption worldwide [1]. Air transportation has grown in importance thanks to the time it saves us in daily life. Correspondingly, the number of aircraft in service has increased and the contribution of air transportation to energy utilization has increased more than expected. Thus, aircraft propulsion systems, especially gas turbine engines, have caught the attention of researchers dealing with thermal engineering. However, a number of early research papers emphasize the need to use exergy in the course of aircraft propulsion systems development processes as an optimizing and design tool to achieve more efficient and environmentally friendly systems [16,17]. With respect to this, numerous aircraft gas turbine engines have been investigated using exergy. Turgut et al. [18] contributed to the literature by examining a turbofan engine at sea level condition with the aid of exergy. The fan and hot section nozzle were found to be the most irreversible

* Corresponding author. Tel.: +90 5347661416.
E-mail address: ysohret@gmail.com (Y. Şöhret).

http://dx.doi.org/10.1016/j.energy.2015.09.081
0360-5442/

Nomenclature

$\dot{E}$	exergy rate (kW)
$\dot{IP}$	improvement potential rate (kW)
$\dot{Q}$	heat transfer rate (kW)
$\overline{R}$	universal gas constant
$\dot{W}$	work rate or power (kW)
c_p	specific heat capacity under constant pressure (kJ kg^{-1} K^{-1})
$\dot{e}$	specific exergy rate (kW kg^{-1})
$\dot{m}$	mass flow rate (kg s^{-1})
F	thrust (kN)
FAR	fuel-air ratio
h	enthalpy (kJ kg^{-1})
LHV	lower heating value (kJ kg^{-1})
M	molar weight (kg kmol^{-1})
N	mole number (mole)
NGV	nozzle guide vanes
P	pressure (kPa)
T	temperature (K)
TSFC	thrust specific fuel consumption (kg kN^{-1} h^{-1})
V	speed (m s^{-1})
g	gravity (m s^{-2})
x	mole fraction
y	variable
w	uncertainty
z	altitude from reference (m)

Subscripts

0	dead state conditions
air	specification of air
D	destruction
F	exergetic fuel
f	fuel
flight	flight
gas	exhaust gas
i	engine station number
in	inlet section
k	kth ingredient of the mixture
L	loss
mix	mixture
out	outlet section
P	exergetic product

Superscripts

CH	chemical
KN	kinetic
PH	physical
PT	potential

Abbreviations

AC	air compressor
CC	combustion chamber
HPT	high pressure turbine
LPT	low pressure turbine
TFE	turbofan engine
UAV	unmanned aerial vehicle

Greek letters

δ	fuel depletion rate
ε	exergy efficiency (%)
ξ	productivity lack
χ	relative irreversibility (%)

components of the engine as a result of the study. In Ref. [19], fundamental exergy relationships were introduced to evaluate the performance of an aerial vehicle for each phase point of a flight. Exergy balance equations and entropy functions were developed regarding the impact of drag and lift forces on the energy consumption of the propulsion system. Tona et al. [20] present the exergy parameters of a turbofan engine in addition to an economic evaluation. Within this scope, the variation in exergy efficiency for each component was obtained at the take-off, climb, cruise, descent, holding and landing phases of a flight. Depending on the exergy analysis, researchers also performed a cost analysis of the evaluated engine. Turan [21] discusses the effect of certain engine design parameters, for example pressure ratio, turbine inlet temperature and flight Mach number, on the exergetic performance of a turbojet engine. This study may be considered a milestone as the first exergy analysis of an UAV (unmanned aerial vehicle) applicable jet engine. As a result of this study, it was concluded that the exergy efficiency of components and the engine improve, in relation to an increase in Mach number. Another paper [22] reveals the exergetic performance and economic aspects of a CT7-9C turboprop engine. The compressor, combustion chamber, gas turbine and power turbine components are evaluated within this framework. Balli and Hepbasli [23] conducted an exergy analysis of another turboprop engine, mostly used for military applications. The engine was investigated under different operating modes, such as 75% and 100% loads, military and take-off. The dependence of exergetic characteristics of the engine on operating mode was presented. Unlike in previous studies, uncertainty analyses were also performed in this study. In Ref. [24] the performance of a J85-GE-21 turbojet engine with afterburner was evaluated at sea level conditions and 11000 m altitudes based on the exergy analysis method. A decrease of exergy efficiency, based on reducing inlet air speed, was noted by the authors. In addition, the study concluded that the loss of exergy efficiency was 0.45% with a 1 °C temperature decrease. Balli [25] presented the impact of an afterburner on the exergetic performance of an experimental turbojet engine. The exergy efficiency of the investigated engine was calculated to be 29.81% and 22.77% for military and afterburner modes, respectively. A genetic algorithm was developed for the exergy-based optimization of a turbofan engine by Tai et al. [26]. Engine cycle analysis equations were combined with an exergy approach in this context. A 3.3%–11.0% increase in specific thrust generation was confirmed at the expense of 1.5%–2.3% of extra fuel consumption with the aid of thermodynamic optimization.

Exergy analyses of gas turbine engines operated on UAVs (unmanned aerial vehicles) are scarce in the literature. Related to progress in this field gas turbine engines used for UAVs should be investigated from the view point of exergy. For this purpose, the current study aims to contribute to the literature by examining a turbofan engine which is the main power unit of an UAV. Within this scope, exergy parameters (exergy efficiency, exergy destruction rate, improvement potential rate, productivity lack, and fuel depletion rate) for each component of the engine are presented based on obtained results from an engine model for a mission flight. The exergy analysis of the engine is conducted for a typical surveillance mission flight of the UAV.