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Exergy as a useful tool for the performance assessment of aircraft gas turbine engines: A key review

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It is known that aircraft gas turbine engines operate according to thermodynamic principles. Exergy is considered a very useful tool for assessing machines working on the basis of thermodynamics. In the current study, exergy-based assessment methodologies are initially explained in detail. A literature overview is then presented. According to the literature overview, turbofans may be described as the most investigated type of aircraft gas turbine engines. The combustion chamber is found to be the most irreversible component, and the gas turbine component needs less exergetic improvement compared to all other components of an aircraft gas turbine engine. Finally, the need for analyses of exergy, exergo-economic, exergo-environmental and exergo-sustainability for aircraft gas turbine engines is emphasized. A lack of agreement on exergy analysis paradigms and assumptions is noted by the authors. Exergy analyses of aircraft gas turbine engines, fed with conventional fuel as well as alternative fuel using advanced exergy analysis methodology to understand the interaction among components, are suggested to those interested in thermal engineering, aerospace engineering and environmental sciences.

Contents

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Nomenclature

$\dot{Y}_k$	kth component related environmental impact rate (mPts h^{-1})
$\dot{Z}_k$	kth component cost (US$ h^{-1})
$\dot{B}$	Environmental impact rate (mPts h^{-1})
$\dot{E}$	Exergy rate (kW)
$\dot{Q}$	Heat flow rate (kW)
$\bar{R}$	Universal gas constant (kJ kmol^{-1} K^{-1})
$\dot{W}$	Work rate or power (kW)
c_p	Constant pressure specific heat capacity (kJ kg^{-1} K^{-1})
$\bar{e}$	Molar specific exergy (kJ kmol^{-1})
f_{ed}	Exergy destruction factor
$\dot{m}$	Mass flow rate (kg s^{-1})
r_{eef}	Environmental effect factor
r_{re}	Recoverable exergy rate
r_{we}	Waste exergy ratio
e	Specific exergy (kJ kg^{-1})

Subscripts

0	Ambient condition
1,2,3…	Station number
a	Air
D	Destruction
exh	Exhaust
F	Exergetic fuel
f	Fuel
g	Gas
in	Inlet
k	*kth* Component
L	Loss
out	Outlet
P	Exergetic product

Superscripts

ph	Physical
ch	Chemical
k	Kinetic
p	Potential

Greek Letters

Θ	Exergetic sustainability index
ε	Exergy efficiency

Acronyms

AC	Air compressor
CC	Combustion chamber
DF	Ducted fan
GT	Gas turbine
LHV	Lower heating value
NZ	Exhaust nozzle
PT	Power turbine

1. Introduction

In accordance with the lexical meaning of thermodynamics, it can be described as efforts to convert heat into power. Thermodynamics is a science, which also deals with the utilization of energy resources effectively and efficiently. However, developments in the 21st century and the rise of energy demand made utilizing energy efficiently more and more important. For this reason, people interested in thermal engineering are concerned with this issue.

Two natural laws provide the basis of thermodynamics. These fundamental laws are well-known as the first and second law of thermodynamics. The first law of thermodynamics deliberates energy conservation and asserts that energy can change form, though the amount of the total energy is always constant in the course of a thermal process. An evaluation of any thermal system or process in the framework of the first law provides insight into how energy is consumed or morphed into another form. It is easy to see this in our daily lives with power plants, which generate electricity from various energy sources, air conditioners and even the human body [1–3].

In the late 1950s, the Slovenian scientist Zoran Rant defined the term exergy as 'technical working capacity'. After years of discussion, Gibbs stated exergy to be S in a certain state S_A is the maximum theoretical useful work obtained if S is brought into thermodynamic equilibrium with the environment by means of ideal processes in which the system interacts only with this environment'. After the 1970s, the definition of the term exergy improved, and the well-known exergy definition emerged. Within modern thermodynamics, the definition of exergy is accepted as being the maximum shaft work that can be done by the composite of a system and in a specified reference environment that is assumed to be infinite, in equilibrium, and ultimately enclosing all other systems. Following the 1980s, the studies of Szargut [4] and Kotas [5] led to progress in thermal engineering. Later, exergy-based thermodynamic assessment of various thermal processes and systems attracted intensive attention [6]. Bejan [7], Cengel [8] and Dincer [9] had a great influence on the evolution of thermodynamics and the term exergy. Studies performed post 1990 show how to benefit from the term exergy for evaluation of thermal processes and systems.

Exergy assessment is no longer only a method to understand energy utilization quality. It is also a useful tool to analyse and optimize thermal systems with regard to economics, environmental and sustainability issues. The exergo-environmental assessment method attracts attention when common environmental issues (e.g. ozone depletion, global warming) gain importance based on the strong bond between energy consumption and ecology. However, air pollutants come into existence as a result of energy generation, transformation and transportation processes. Likewise, sustainable development and sustainable energy technology related to environmental issues are great concerns. However, it is essential to deplete energy sources efficiently for sustainability and a reduction of the impact on the environment thermal processes. It is obvious that thermal systems with higher exergy efficiency affect the environment less and contribute more to sustainable development [9–11].

Considering the working principles of aircraft gas turbine engines is sufficient to comprehend the significance of an exergy-based approach. The working fluid of a system carries exergy as well as energy. In any type of aircraft gas turbine engine, exergy is destroyed or entropy is generated throughout the power-generation process, as with other thermal systems. Thus, exergy analysis and optimization are required for aircraft gas turbine engines. In addition, exergy analysis forms a basis for environmental and economic improvement and for the optimization of aircraft gas turbine engines as mentioned above [12–19].

The current paper is intended to show the state of the art and emphasize the necessity of exergy-based analyses for aircraft gas turbine engines. From this point of view, previous accessible