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Assessment of degradation effects for an aircraft engine considering exergy analysis

M. Ziya Sogut [a, *], Enver Yalcin [b], T. Hikmet Karakoc [a]

[a] *Faculty of Aeronautics and Astronautics, Anadolu University, TR-26470, Eskisehir, Turkey*
[b] *Department of Mechanical Engineering, Engineering Faculty, Balikesir University, TR-10145, Balikesir, Turkey*

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ABSTRACT

Despite the improvements in engine technology, the combustion processes and wear occurred in engine components affect performance adversely. The turbine and compressor fouling, degradation mechanisms such as erosion, corrosion and mechanical clearances depending on time and thermal expansion may occur. The engine output performance and the operational efficiency of each component are affected directly by these negative cases. In this study, effects of power losses, defined by degradation mechanisms which were encountered during the compressor and turbine life cycles, on system performance were handled. Energy and exergy analysis of the loss effects in each component, defined taking into consideration the periodical component replacements, were evaluated separately. At the end of the study, the loss effects dependent on fuel consumption of turbofan engine taken as reference during the flight period were also evaluated.

1. Introduction

A sustainable and steady performance effect in motor technologies or energy systems is considered possible under reversible conditions. But, this is impossible because of irreversibilities such as friction, material fatigue and other system losses emerged during the life cycle of systems taken into consideration. This expression applies to turbines as well. In gas turbines used as aircraft engines, the fuel consumption of the engine is directly affected by these irreversibilities. From a different point of view, these losses can be considered as an important potential to increase operation efficiency.

Energy usage of aviation industry with a share of 10% in the total transport sector is an indispensable element of modern economy and sustainable development [1]. Also, this sector, which has about 2% of total greenhouse gas emissions in the world, is also increasing rapidly effect of its emissions with increasing demand [1]. The efforts of mitigation in the emission share of this sector have been supported by studies on aircraft engine technology. But, the many studies, on mainly material preferences, have also been done to reduce degradation effects together with technological improvements [2–4].

Despite the improvements in engine technology, the combustion processes and wear occurred in engine components adversely affect performance. Especially, combustion and fuel characteristics can be displayed as the most important component of emission threat. However, this effect increases indirectly due to the wear and tear for life cycle of the turbine and compressor. These two components that are high speed operation and continuity of burned product flow at high temperature in the combustion chamber can be seen as reasons of deterioration. In the process, this deterioration leads to higher fuel consumption in order to achieve the desired thrust, accordingly higher operating and maintenance costs. Adjustment of these processes in the normal structure may also be costly and consuming more time in terms of operating strategies [5].

For this reason, degradation is a major problem in engine technologies or energy consuming system components. The basic concept of degradation for gas turbines has gained importance in the engine design and development process. Degradation can be grouped into three basic structures. These are recoverable deterioration, unrecoverable deterioration and permanent deterioration. The many studies on this subject can be seen in the literature [6–10]. For example, Zhou et al., in their studies, the failure modes of power machines examined the failure of non-operating equipment or the performance degradation of power machines. In the

* Corresponding author.
E-mail addresses: mzsogut@gmail.com (M.Z. Sogut), eyalcin@balikesir.edu.tr (E. Yalcin), hikmetkarakoc@gmail.com (T.H. Karakoc).

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Nomenclature

$\dot{E}$	energy (kW)
$\dot{E}x$	exergy (kW)
h	enthalpy (kJ/kg)
$\dot{IP}$	improvement potential for exergy (kW)
ke	kinetic energy (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
pe	potential energy (kJ/kg)
$\dot{Q}$	heat transfer (kW)
s	specific entropy (kJ/kgK)
T	temperature (K,°C)
$\dot{W}$	shaft work, work (kW)
Ton	Ton CO_2 per TJ energy

Greek letters

η_{Ex}	exergy (second law) efficiency
ψ	the flow specific exergy
θ_{CO_2}	CO_2 emission factor

Indices

in	input
kin	kinetic energy
out	outlet, existing
dest	destruction
Pot	potential
ph	physical
ch	chemical
gen	generation
0	dead state

study, they stated that safety, economic and environmental effects should not be ignored when performance declines occurred [11]. Verda presented a study on the prediction of the fuel effect on performance loss in power plants. In his study, he developed a prognosis procedure based on productivity. Thus, he provided a prediction of consumption with 5% error [12].

Structural degradation, especially in the aircraft, is a process that must be closely monitored during maintenance processes. For this reason, material changing periods for these processes have been given in maintenance manual with all component aspects. Although the studies related with local material or system degradation in the literature, there are quite limited studies describing direct performance impacts. This is considered as a rather complicated issue. Indeed, the ability to identify the direct effects of fatigue or loss increases on components requires extensive experimental work. However, the evaluation of these potential effects can be made by thermodynamic analysis together with numerical models. In this study, the effects of performance reduction on system efficiency were investigated in four case conditions defined by degradation effects.

2. Degradation in gas turbine systems

To maintain the gas turbines at the desired thrust levels, the engine is operated at high speed, which directly affects the life cycle of the components. All systems having thermal and mechanical components are facing with the effects of wear and tear during the life cycle. A gas turbine is a complicated system having main core elements like compressor, turbine and combustion chamber together with many subsystems and components. The turbofan engine seen in Fig. 1 is considered in this context. Turbofan engines with low fuel consumption are defined as more efficient engines according to the turbojet engine in engine development process. In this study, the degradation effects for a turbofan engine were assessed for a flight period taken as reference.

All aircraft engines exhibits the effects of degradation defined in the maintenance process over time. For example Kurz studied on the importance of the recognition of certain degradation problems [14]. Like this, the many of studies about the mechanisms that cause degradation have been done [15–17]. These problems and changes can be stated briefly as follows,

a. The changes on the blade surface due to fouling-induced erosion and the dynamic problems caused by them. Fouling causes deterioration especially on the airfoil profiles. Particulates in the exhaust gas and oil resulting from combustion adhere to the airfoil surfaces and as a result of this, they change airfoil profile over time. The hot corrosion that occurs in this process creates material loss through chemical reactions. These structural reactions lead to deformations such as spalling and cracking on the material surface. As a result of partial removal of some particulates due to spalling and then sloughing due to increased air velocities, erosion can be seen. In some cases, this effect may be greater than 20 μm. Components with risk, which is considered in engine maintenance processes, are made periodic maintenance. Damage is the threat that pollutants create in the flow path as a result of impact in high velocity flows. If the airborne particles entrained with inlet air, they cause damage to the compressor through either erosion or impact. Ruptures in fuel nozzles or carbon surface breaks create problems in turbines and their components. Abrasion is a problem that is especially occurring on rotating surfaces. Although a certain amount of wear is allowed on such surfaces, it causes a significant loss over time [14,18].
b. Mechanical clearances and their impact on the flow (especially deterioration in the seal geometry). The increasing of clearance leads losses of pressure and stall margin and also causes choke at lower flow [19]. On the other hand, it is recommended to increase the end clearance to recompense thermal expansion.
c. Changes in combustion systems based on many reasons. Combustion processes are the most frequently encountered components with degradation effects. This leads to deformation in all materials, especially as an effect starting from the head points under high velocity and heat flow conditions. For this purpose, the life processes of the turbine and rotor blades are extended via local solutions such as turbine cooling. However, this is an important problem at high density [18].

All these parameters are important to evaluate the actual performance of the gas turbine by considering time factor. For this purpose, the effect of degradation on performance should be investigated. Firstly, the degradation behaviours and their mechanisms should be defined. The most common degradations can be defined as the blade (airfoil) pollution, pitting on the blade surface, the rising of the blade clearances, the rotor imbalance caused by blade clearances, nozzle hoarse, unstable airflow, low speeds and higher ambient temperatures [17,20]. When these behaviour processes are considered as gas turbine degradation mechanism in a general structure, briefly, they can be classified as given below as fouling, corrosion, oxidation and hot corrosion, erosion and wear, coalescence of particles and mechanical degradation. When all these structural disorders are taken into account, they can be