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## ORIGINAL ARTICLE

# A comprehensive approach to understanding irreversibility in a turbojet

Yasin Şöhret

Süleyman Demirel University, Isparta TR-32700, Turkey

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## KEYWORDS

Advanced exergy analysis;  
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**Abstract** Regarding interest in and concerns about high efficiency in recent times, an irreversibility assessment of energy conversion systems is significant. Turbojets, a type of energy conversion system, are widely used to provide thrust for aerial vehicles, such as military aircraft missiles, commercial aircraft and so on. From this point of view, the current study aims to introduce a comprehensive irreversibility assessment methodology exemplification for a turbojet. First of all, a basic irreversibility assessment methodology is explained with an application. Following this, a comprehensive assessment is performed. Within this framework, a number of a novel measures are defined by derivations in addition to previously well-known indicators. These measures are beneficial for the decomposition of the irreversibility in a turbojet and its components. At the end of the study, the highest endogenous irreversibility is determined to be in the turbine component of the turbojet engine whereas the highest avoidable irreversibility is found to be in the compressor component of the turbojet engine. The current paper is considered to be of use for researchers and scientists interested in aero-engine performance, thermal engineering and aerospace engineering.

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## 1. Introduction

For centuries jet engines have been the main power system of aerial vehicles. In particular, after World War Two, significant advances in jet engines have occurred. Despite progress made in material and thermal sciences, jet engine technology has not yet been finalized. The main

E-mail address: ysohret@gmail.com

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**Nomenclature**

$\dot{E}$	exergy rate (unit: kW)
$\dot{F}$	thrust rate (unit: kW)
$\dot{m}$	mass rate (unit: $\text{kg} \cdot \text{s}^{-1}$ )
$c_p$	specific heat capacity under constant pressure (unit: $\text{kJ} \cdot (\text{kg} \cdot \text{K})^{-1}$ )
$e$	specific exergy rate (unit: $\text{kW} \cdot \text{kg}^{-1}$ )
$g$	acceleration of gravity (unit: $\text{m} \cdot \text{s}^{-2}$ )
$LHV$	lower heating value (unit: $\text{kJ} \cdot \text{kg}^{-1}$ )
$M$	molar weight (unit: $\text{kmol} \cdot \text{kg}^{-1}$ )
$Ma$	Mach number
$N$	mole number
$P$	pressure (unit: kPa)
$R$	molar gas constant (unit: $\text{J}/(\text{mol} \cdot \text{K})$ )
$\dot{S}$	entropy rate (unit: $\text{kW} \cdot \text{K}^{-1}$ )
$T$	temperature (unit: K)

$V$  velocity (unit:  $\text{m} \cdot \text{s}^{-1}$ )

**Greek symbols**

$\Lambda$	unavoidability indicator
$\varepsilon$	exergy efficiency (unit: %)
$\eta$	efficiency (unit: %)
$\pi$	compression or expansion ratio (unit: rad/s)

**Subscripts**

$D$	destruction
$F$	fuel
$gen$	generation
$L$	loss
$P$	product

issue faced with up to now is a failure to reach expected high efficiency.

A methodology commonly-employed in thermal engineering, namely exergy analysis, is strongly recommended for use in performance evaluation and as a design tool for jet engines in many texts [1,2]. From this point of view, the jet engine, a type of energy conversion system working on the basis of the Brayton cycle, can be explained by the first and second laws of thermodynamics. Therefore, evaluating a jet engine with the aid of exergy is feasible, as it is a method integrating both the first and second laws of thermodynamics.

The term exergy is defined as the achievable maximum work of an examined system in modern thermodynamics [3]. That is the starting point of exergy analysis. Exergy analysis is used to reveal the potential and the upper limits of an evaluated system under actual conditions. In addition, it is beneficial for an understanding of irreversibility in the system under investigation [3–5].

Understanding irreversibility in a jet engine by means of exergy analysis can help us to spot efficiency improvements of an engine. While measuring the quality of energy consumption, exergy analysis yields the amount, location and variety of energy consumption as a result. For this purpose, many research studies have been introduced into the literature [6]. Some previous studies report the benefits of exergy analysis as a jet engine design and optimization tool [7–11]. However, papers accessed in the literature discuss the performance of various types of jet engines under different operating conditions [12–25]. Overall, from these studies, the combustor is determined to be the most irreversible component of all jet engine types, whereas the least irreversible is identified to be the turbine compared to the other components.

Exergy analysis is limited in determining only the degree of reversibility of jet engine components, although it is beneficial in revealing irreversibility as mentioned earlier. Therefore, it is necessary to evaluate a jet engine in more

detail using a more powerful tool. A novel methodology recently presented in favor of current advances in thermal engineering and science, namely advanced exergy, enables us to understand irreversibility comprehensively and to associate relationships among the components of irreversibility [26,27].

In the accessible literature, advanced exergy analysis of numerous systems can be found [28–40]. Advanced exergy analysis application to various jet engines may be accessed in the literature as well as other energy conversion systems [41–43]. The earliest of these evaluates the core section of a turbofan engine using advanced exergy methodology [41]. After conventional exergy analysis of the engine, the exergy destruction rate is split into avoidable and unavoidable parts in addition to endogenous and exogenous parts. At the end of the paper, the highest exergy destruction is found to have occurred in the combustion chamber with a high ratio of unavoidable endogenous. Another research paper focuses on the advanced exergy analysis of a turboprop type aircraft engine [42]. It identifies the weak association among components as a result of an 86% rate of endogenous exergy destruction. Balli [43] presents conventional and advanced exergy analyses of a military turbojet engine together. The analyses are performed for afterburning and military operating modes of the engine, with the results then being compared.

The literature survey reveals the lack of a detailed irreversibility assessment of aero-engines. In the current study, advanced exergy methodology is explained in detail and is used to spot irreversibility in an engine and to understand the relationship among the engine components. The methodology is exemplified with a turbojet engine operating under off-design conditions for this purpose.

## 2. General description of the turbojet

The evaluated turbojet engine is a simple gas turbine engine. It comprises a compressor, combustor, turbine and exhaust nozzle, as illustrated in Figure 1.

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