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EXERGO-SUSTAINABILITY ANALYSIS AND ECOLOGICAL FUNCTION OF A SIMPLE GAS TURBINE AERO-ENGINE

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ABSTRACT

Nowadays, many environmental issues are of concern as a result of conventional energy resources utilization in addition to a rise in energy costs dependent on the rapid consumption of resources. Therefore, sustainability is an important term for the utilization of energy resources. The aviation industry is known to be responsible for 3% of total CO_2 emissions concerning global warming. This forces us to investigate the aviation industry, specifically gas turbine aero-engines. Gas turbine aero-engines, working according to the principles of thermodynamics, similar to other energy conversion and generation systems can be evaluated using the first and second laws of thermodynamics. Integrated employment of the first and second laws of thermodynamics, namely exergy analysis, is an effective method for performance evaluation. Additionally, exergo-sustainability also yields beneficial results. In the framework of the current paper, ecological function is defined for a simple gas turbine aero-engine, while exergo-sustainability assessment methodology is also explained. Exergy efficiency of the compressor, combustor, gas turbine and nozzle, as components of a gas turbine aero-engine, is found to be 91.58%, 57.41%, 97.96%, and 61.25%, respectively. On the other hand, the sustainability measures of the evaluated gas turbine aero-engine in order of exergy efficiency, waste exergy ratio, recoverable exergy rate, exergy destruction factor, environmental effect factor and sustainability index are calculated to be 0.28, 0.71, 0.00, 0.69, 2.45, and 0.40, respectively whereas the ecological function is found to be -8732.21 kW.

Keywords: *Aircraft, Aviation, Ecological function, Exergy, Gas turbine, Sustainability*

INTRODUCTION

It is known that the aviation industry is growing rapidly. It is gaining importance for air transportation, particularly in Turkey. This yields an increase in energy consumption and directly or indirectly impacts on the environment as well as on economic expansion. A lack of energy resources and a rise in costs are major concerns of many industries and are also issues for aviation [1-4]. A rapid depletion of energy resources, particularly intensely consumed petroleum derived fuels, namely conventional fuels, is a global issue. Kerosene aviation fuel is a kind of petroleum derived fuel and its cost increases annually as a result of energy crises [5, 6]. Regarding such realities, the aviation industry is driven to use alternative and renewable energy technologies in aerial vehicles and aircraft. Ongoing research and various studies have not yet achieved the expected level of technology to meet the demands of commercial passenger and cargo aircraft [7, 8]. As a result, improvement and efficiency augmentation of existing aircraft propulsion systems seem to be obvious solutions. The working principles of gas turbine aero-engines, much like many other energy conversion systems, can be explained by the laws of thermodynamics. From this perspective, thermodynamic analysis and related methods are beneficial with regard to improving the performance and efficient augmentation of gas turbine aero-engines [9-11].

Many studies on performance, efficiency, economy, environmental impact and sustainability of aero-engines have been presented to the literature up to now [11]. Ehyai et al. [12] evaluated the performance of an after-burning jet engine by means of exergy analysis. This study was performed under two altitude conditions and two engine inlet air velocity cases. Another important aspect of this study is a consideration of potential and kinetic energy and exergy alternations during the analysis. At the end of the study, exergy efficiency degradation was determined as engine inlet velocity decreased. In Ref. [13], a turboprop type engine was assessed thermodynamically. The study reveals the energy and exergy efficiencies of the engine to be 30.7% and 29.2%, respectively. In a paper by Balli and Hepbasli [14] a turboprop engine type was also investigated. The engine was examined under two different operating conditions with four different engine loads. At the end of the study, the impact of both kinetic and potential energy and exergy variations on exergy efficiency were ascertained. Ref. [15] presents the specific fuel consumption, fuel depletion rate, productivity lack and improvement potential of a turbofan engine and its components. Tai et al. [16] developed a code based on exergy analysis to evaluate and

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optimize the performance of a turbofan engine in their study. Using this approach, researchers optimized engine design parameters affecting engine performance. In another paper [17], a genetic algorithm was used to determine performance measures of a turboprop engine and its components for different cases. Ref. [18] deals with the effect of biofuel utilization on thermodynamic performance of a turboprop engine. At the end of the research, exergy efficiency improvement, dependent on the amount of methanol in blends of methanol and kerosene, was reported. The turbofan engine of an UAV during a full mission flight was examined with the aid of exergy by Sohret et al. [19]. In this case, performance parameters, such as exergy efficiency, improvement potential, exergy destruction rate and so on were introduced for each phase of a flight. The highest exergy destruction was revealed to occur during the take-off and climb-out phases of a flight. An exergy analysis of a gas turbine engine of a helicopter is presented in Ref. [20]. Through this research the authors intended to contribute to on-going performance improvement research on the evaluated engine. Ref. [21] compares biofuel and kerosene utilization in a miniature gas turbine engine. In this regard, exergy and exergo-economic analyses were performed for the whole engine in addition to its components. In addition to the performance evaluation of various aero-engines, exergo-sustainability analyses of these can also be found in the accessible literature [22-26].

In thermal engineering, ecologic assessments of different types of systems have been presented to the literature [27-32]. The most prominent parameter proposed for this purpose is ecological function [27, 33]. However, ecologic aspects of any gas turbine aero-engine have not yet been discussed. From this point of view, the current study intends to draw attention to ecologic considerations while discussing sustainable design and sustainability assessment integrated to performance evaluation of aero-engines. For this purpose, simple gas turbine aero-engine performance is evaluated in terms of sustainability and thermodynamics. In contrast to previous studies, ecological function is defined for a simple gas turbine aero-engine for the first time. The author also intends to contribute to ongoing research of an indigenous unmanned aerial vehicle propulsion system being developed in Turkey by presenting this novel approach to the literature.

MATERIALS AND METHOD

Simple Gas Turbine Aero-Engine Cycle

A simple gas turbine engine, as illustrated in Fig. 1, is composed of an air inlet, air compressor, combustor chamber, turbine and exhaust nozzle. The flow of sucked air from the ambient air is regulated in the air inlet and then directed through the air compressor. The temperature and pressure of the air rise at the end of the compression process and it passes through the combustion chamber. The chemical reaction of air and fuel in the combustion chamber yields combustion gases with heat loaded. The high energy capacity of the combustion gases is used to generate the required power for the air compressor and other accessories. Finally, in the exhaust nozzle the speed of the combustion gases is increased by a section area decrease to generate thrust [34, 35].

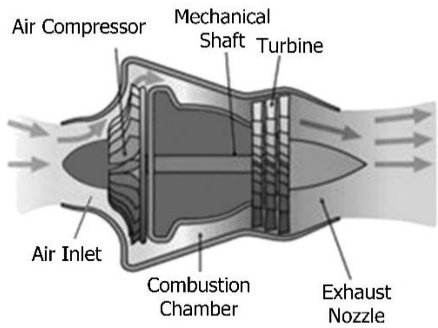

Figure 1. Schematic of a simple gas turbine aero-engine [35]

A simple gas turbine aero-engine works in accordance with the Brayton cycle. Cycle calculations of a simple gas turbine aero-engine under actual operating conditions are performed regarding the T-s diagram shown in Fig. 2. Herein, station numbers 0, 02, 03, 04, 05 and 06 relate to ambient, compressor inlet, combustion chamber inlet, turbine inlet, exhaust nozzle inlet and ambient air, respectively. The first law analysis of an actual gas turbine engine can be found in many textbooks [34, 35].

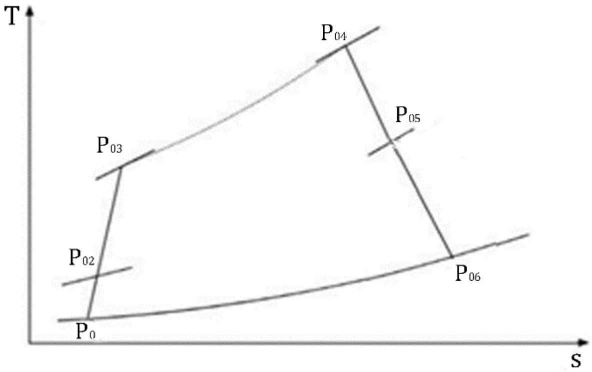

Figure 2. T-s diagram of an actual simple gas turbine aero-engine [35]

Exergy Analysis

For exergy analysis of a simple gas turbine aero-engine, the following governing equations (mass balance, energy conversion and exergy balance respectively) are first written [36]:

$$\sum \dot{m}_{in} - \sum \dot{m}_{out} = 0 \tag{1}$$

$$\sum \dot{m}_{in}(h + ke + pe)_{in} - \sum \dot{m}_{out}(h + ke + pe)_{out} + \sum \dot{Q} - \sum \dot{W} = 0 \tag{2}$$

$$\sum \dot{Ex}_{in} - \sum \dot{Ex}_{out} - \sum \dot{Ex}_{dest} - \sum \dot{Ex}_{loss} = 0 \tag{3}$$

Herein $\dot{m}$, h, ke, pe, $\dot{Q}$, $\dot{W}$, and $\dot{Ex}$ represent mass flow rate, specific enthalpy, specific kinetic energy, specific potential energy, heat flux rate, power output and exergy rate. The exergy of a flow is known to be composed of chemical, physical, potential and kinetic components: [36]:

$$\dot{Ex} = \dot{Ex}^{KN} + \dot{Ex}^{PT} + \dot{Ex}^{PH} + \dot{Ex}^{CH} \tag{4}$$

The potential and kinetic exergies of a flow are equal to potential and kinetic energies. However, the potential and kinetic exergies of the flow are mostly too small compared to physical and chemical exergies. As a result, the potential and kinetic exergies of the flow are commonly disregarded. The physical exergy of the flow is stated as follows [36]:

$$\dot{Ex}^{PH} = \dot{m}_{\mathrm{i}}\left[c_{p,i}(T_i - T_0) - T_0\left(c_{p,i}\ln\frac{T_i}{T_0} - R\ln\frac{P_i}{P_0}\right)\right] \tag{5}$$

Herein, the specific heat capacity of the fluid under constant pressure should be noted to be a function of temperature. On the other hand, the chemical exergy of a hydrocarbon fuel and a gaseous mixture can be expressed by the following equations [36]:

$$\dot{ex}_{fuel}^{CH} = LHV\big[1.0401 + \big(0.1728(H/C)_{fuel}\big)\big] \tag{6}$$

$$ex_{mix}^{CH} = \frac{\left[\sum\left((N_j/\sum N_j)\overline{ex}_j^{CH}\right) + \bar{R}T_0\sum(N_j/\sum N_j)\ln(N_j/\sum N_j)\right]}{M_{mix}} \tag{7}$$

in Eq. 6 LHV is the lower heating value of the fuel and H/C is the hydrogen-carbon rate of the fuel whereas N denotes the mole fraction of the exhaust gas ingredient and M_{mix} is the molar weight of the exhaust gas mixture in Eq. 7.

Table 1. Derived exergy statements for a simple gas turbine aero-engine and its components

	$\dot{Ex}_{in}$	$\dot{Ex}_{out}$
Air compressor	$\dot{Ex}_{02} + \dot{W}_{AC}$	$\dot{Ex}_{03}$
Combustion chamber	$\dot{Ex}_{03} + \dot{Ex}_{fuel}$	$\dot{Ex}_{04}$
Turbine	$\dot{Ex}_{04}$	$\dot{Ex}_{05} + \dot{W}_T$
Exhaust nozzle	$\dot{Ex}_{05}$	$\dot{Ex}_{06}$
Whole engine	$\dot{Ex}_{02} + \dot{Ex}_{fuel}$	$\dot{Ex}_{Thrust}$

In the current paper, the assumptions listed below are made and the equations given in Table 1 are derived for each engine component:

- The engine was operated under steady-state and steady conditions.
- Ideal-gas considerations were applied to the air and combustion gases.
- The combustion reaction was fully completed.
- The chemical formula of the conventional aviation fuel is $C_{11}H_{21}$
- The compressor, combustion chamber, and gas turbine are considered to be adiabatic.
- Changes in kinetic energy, kinetic exergy, potential energy and potential exergy through the engine, except for the exhaust nozzle, were neglected.

Combustion equilibrium for the conventional aviation fuel according to air composition given in Ref. [19] can be written as follows:

$$C_{11}H_{21} + \varphi_1(0.7567\ N_2 + 0.2035\ O_2 + 0.0303\ H_2O + 0.000345CO_2 + 0.000007\ CO) \longrightarrow \varphi_2CO_2 + \varphi_3H_2O + \varphi_4N_2 + \varphi_5O_2$$

Table 2. Combustion reaction constants for the conventional aviation fuel

	φ_1	φ_2	φ_3	φ_4	φ_5
Ideal case	79.85395	11.02795	12.91957	60.42549	0.00000
Actual case	227.86276	11.07975	17.40424	172.42375	30.11927

Performance Indicators

The performance of a system is measured by certain useful indicators with the aid of exergy analysis. Exergy efficiency, the first of these, is the ratio of output exergy to input exergy [29]:

$$\varepsilon = \frac{\dot{Ex}_{out}}{\dot{Ex}_{in}} \tag{8}$$

Another indicator, defined by Van Gool [37] for the first time, is the improvement potential of the system and indicates the amount of reducible exergy destruction:

$$\dot{IP}_{Ex} = (1-\varepsilon)\dot{Ex}_{dest} \tag{9}$$

Relative irreversibility can be understood from its name, and indicates the exergy destruction ratio of any component compared to others [38]:

$$\chi_i = \frac{\dot{Ex}_{dest}}{\sum \dot{Ex}_{dest}} \tag{10}$$

Fuel depletion rate, another performance indicator, is the ratio of exergy destruction within the evaluated component to exergy input of the overall system [38]:

$$\delta_i = \frac{\dot{Ex}_{dest}}{\dot{Ex}_{in,system}} \tag{11}$$

Productivity lack, the last performance measure, is expressed to be the ratio of exergy destruction within the evaluated component to exergy output of the overall system [38]:

$$\xi_i = \frac{\dot{Ex}_{dest}}{\dot{Ex}_{out,system}} \tag{12}$$

Sustainability Indicators

For sustainability evaluation, certain useful indicators are beneficial. These indicators are exergy efficiency, waste exergy ratio, recoverable exergy rate, exergy destruction factor, the environmental effect factor and the sustainability index.

The waste exergy ratio is the ratio of wasted exergy to input exergy [11, 18, 22-26]:

$$r_{waste} = \frac{\dot{Ex}_{\mathrm{waste}}}{\dot{Ex}_{in}} \tag{13}$$

$$\dot{Ex}_{\mathrm{waste}} = \dot{Ex}_{\mathrm{in}} - \dot{Ex}_{\mathrm{thrust}} \tag{14}$$

The recoverable exergy rate indicates the ratio of recoverable amount of wasted exergy to input exergy [11, 18, 22-26]:

$$r_{re} = \frac{\dot{Ex}_{\mathrm{re}}}{\dot{Ex}_{in}} \tag{15}$$

The exergy destruction factor is another indicator and is expressed as follows [11, 18, 22-26]:

$$f_{dest} = \frac{\dot{Ex}_{\mathrm{dest}}}{\dot{Ex}_{in}} \tag{16}$$

The environmental effect factor is the ratio of waste exergy ratio to exergy efficiency [11, 18, 22-26]:

$$r_{\mathrm{eef}} = \frac{\mathrm{r}_{\mathrm{waste}}}{\varepsilon} \tag{17}$$

The last indicator, sustainability index, is found by the following statement [11, 18, 22-26]:

$$\Theta = \frac{1}{r_{eef}} \tag{18}$$

Ecological Function

The ecological function is defined in Ref. [27] for the first time for a Carnot heat engine. At the end of the parametric cycle, a relationship between the useful work output (power) of the system with the availability loss being obtained is calculated and is named the ecological function. The ecological function, also known as the ecological objective function, is expressed as [27, 33]:

$$ECO = \dot{W} - T_0\dot{S}_{gen} \tag{19}$$

$T_0\dot{S}_{gen}$ in Eq. 19 denotes the loss rate of availibilty and is equal to the exergy destruction rate in accordance with the Gouy–Stodola relation [39]:

$$\dot{Ex}_{dest} = T_0\dot{S}_{gen} \tag{20}$$

Considering thrust to be the useful work output of a simple gas turbine aero-engine, Eq. 19 may be re-written for the simple gas turbine aero-engine as follows:

$$ECO = \dot{Ex}_{Thrust} - \dot{Ex}_{dest} \tag{21}$$

RESULTS AND DISCUSSION

In the framework of the current study, the exergy based sustainability assessment methodology and ecological function of a simple gas turbine aero-engine is explained and exemplified. For this purpose, mass and energy conservation, the exergy balance governing balance equations are derived for each component and the whole engine. Following this, sustainability indicators are defined based on results obtained from the exergy analysis. Additionally, ecological function, defined in the literature for any thermal system, is adapted to a simple gas turbine aero-engine for the first time. Cycle data, including mass flow rate, temperature, pressure, energy and exergy rates of each engine station is summarized in Table 3.

Table 3. Cycle data, energy and exergy rates of a simple gas turbine aero-engine and its components [40]

Station	Fluid type	Mass flow rate (kg.s^{-1})	Temperature (K)	Pressure (kPa)	Energy rate* (kW)	Exergy rate* (kW)
0	Air	0.000	242.70	41.06	-	0.00
1	Air	15.000	276.30	61.95	4157.47	461.79
2	Air	15.000	276.30	61.950	4157.47	461.79
3	Air	15.000	525.70	495.60	8153.10	4082.18
31	Fuel	0.351	242.70	41.060	15230.61	20865.80
4	Exhaust gas	15.351	1200.00	475.80	23383.68	14324.16
5	Exhaust gas	15.351	988.20	112.90	18661.91	9310.86
6	Exhaust gas	15.351	748.20	104.20	13270.30	5698.56

***Calculated value.**

At the end of the exergy analysis, the exergy efficiency of the whole engine and its components is found to be 91.58%, 57.41%, 97.96%, 61.25%, and 28.91% for the air compressor, combustion chamber, turbine, exhaust nozzle and whole engine, respectively. For a clearer understanding of this case, Fig. 3 is plotted. From this perspective, the combustion chamber of the engine is determined to be the most irreversible component compared to other components. The highest exergy destruction rate in the combustion chamber leads efficiency drop and improvement potential rate increase of the combustion chamber component.

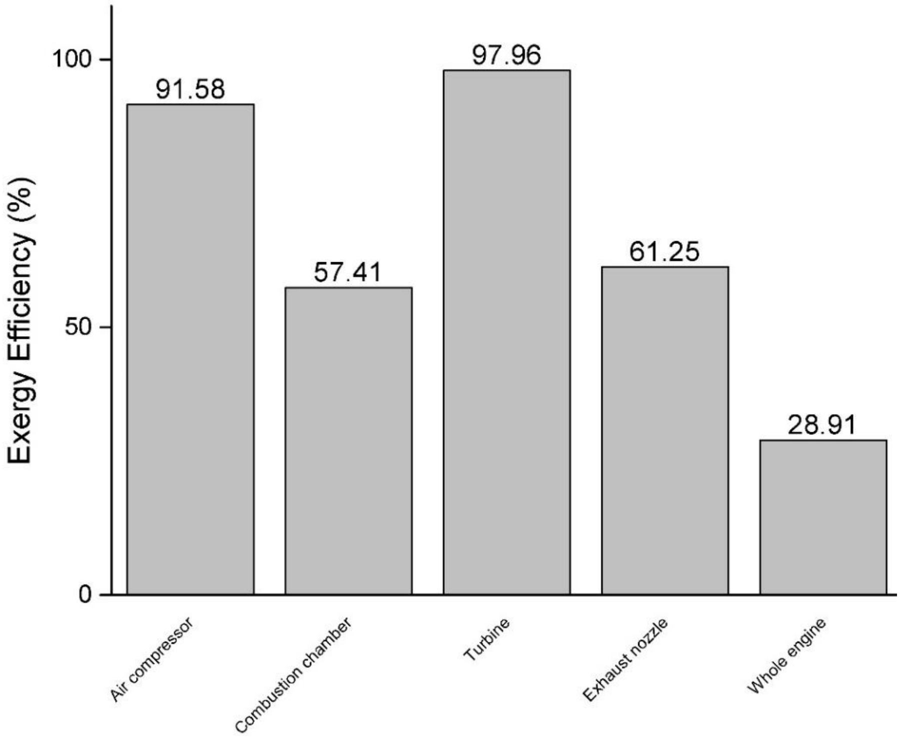

Figure 3. Exergy efficiency variation of the simple gas turbine aero-engine and its components

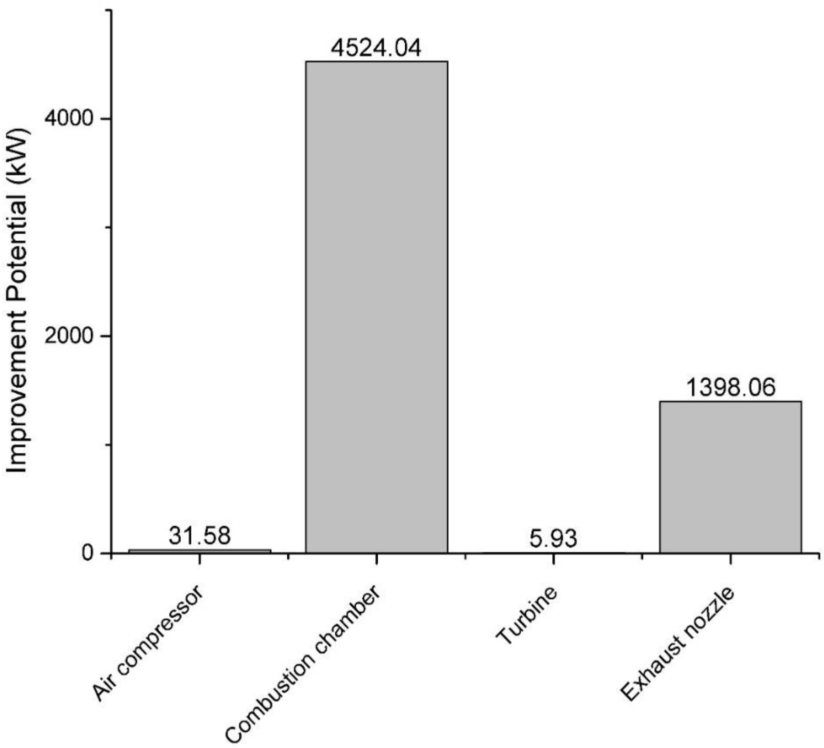

Figure 4. Improvement potential variation of the simple gas turbine aero-engine components

In Fig. 4, the improvement potential of the engine components is plotted. If the improvement potential of the components is evaluated, the air compressor, combustion chamber, turbine and exhaust nozzle have 31.58 kW, 4.52 MW, 5.93 kW and 1.39 MW improvement potential rates, respectively. This finding corresponds with the exergy efficiency results. Potential improvements in the combustion process seem impossible under current technology. This is despite the fact that the design optimization of the combustion chamber may lead to a gain in destructed exergy rate. The low exergy efficiency in the nozzle component associated with a pressure drop yields a high exergy destruction rate and improvement potential. In this regard, directing combustion gases into the nozzle at higher speeds may prevent a pressure drop for thrust generation. Consequently, optimization of nozzle and combustion chamber design is strongly recommended to achieve a more efficient aero-engine.

Fig. 5 demonstrates the relative irreversibility of each component of the aero-engine. As shown in this chart, the relative irreversibility of the air compressor, combustion chamber, turbine and exhaust nozzle components are 2.52%, 71.31%, 1.96% and 24.22%, respectively. In other words, the combustion chamber is the most irreversible component compared to all the others, whereas the turbine has the least irreversibility among all the aero-engine components. According to this chart, the exergy destruction rate distribution among the engine components is once more proven. The fuel depletion variation of the engine components is demonstrated in Fig. 6. Herein, the combustion chamber consumes the highest exergy rate while the fuel depletion rate of the turbine component is the lowest with a value of 0.0055. This situation can be explained with the highest irreversibility rate of the combustion chamber regarding irreversibility in a chemical process (combustion reaction). In this manner, the lack productivity of the combustion chamber is similarly found to be highest for combustion with a value of 0.2003 among all the other components of the aero-engine.

Fig. 8 shows a plot of sustainability indicators of the examined simple gas turbine aero-engine. According to this graph, the exergy efficiency, waste exergy ratio, recoverable exergy rate, exergy destruction factor, environmental effect factor and sustainability index of the aero-engine are calculated to be 0.28912, 0.71117, 0.00, 0.69856, 2.45976, and 0.40654, respectively. Among all indicators the value of the recoverable exergy rate is remarkable. If the released exhaust gases are considered to be non-recoverable and re-usable being zero of the recoverable exergy rate makes sense. As it can be clearly understood, the sustainability index is lower than 0.5. This indicator, being close to zero, shows the necessity for improvements to achieve more efficient and sustainable energy consumption of the evaluated aero-engine. The environmental effect factor is expected to be lower than 1.00, while the sustainability index has as high a value as possible, preferably over 1.00.

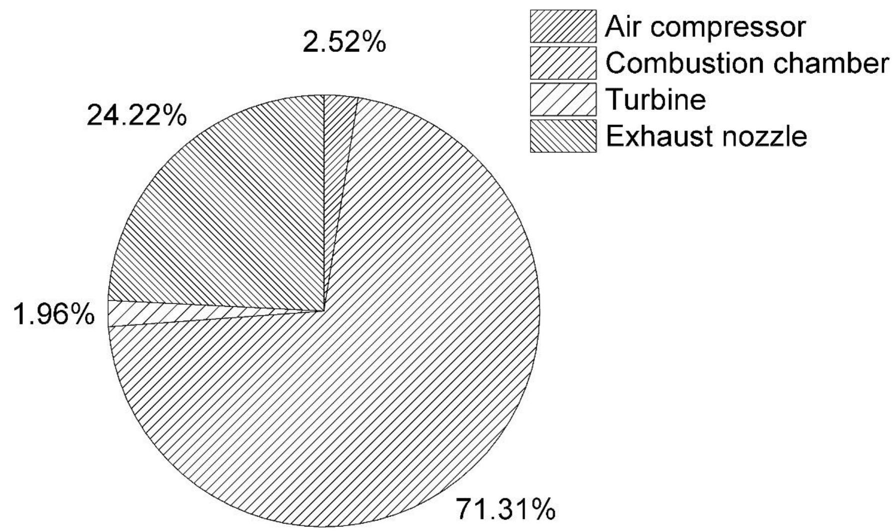

Figure 5. Relative irreversibility of the simple gas turbine aero-engine components

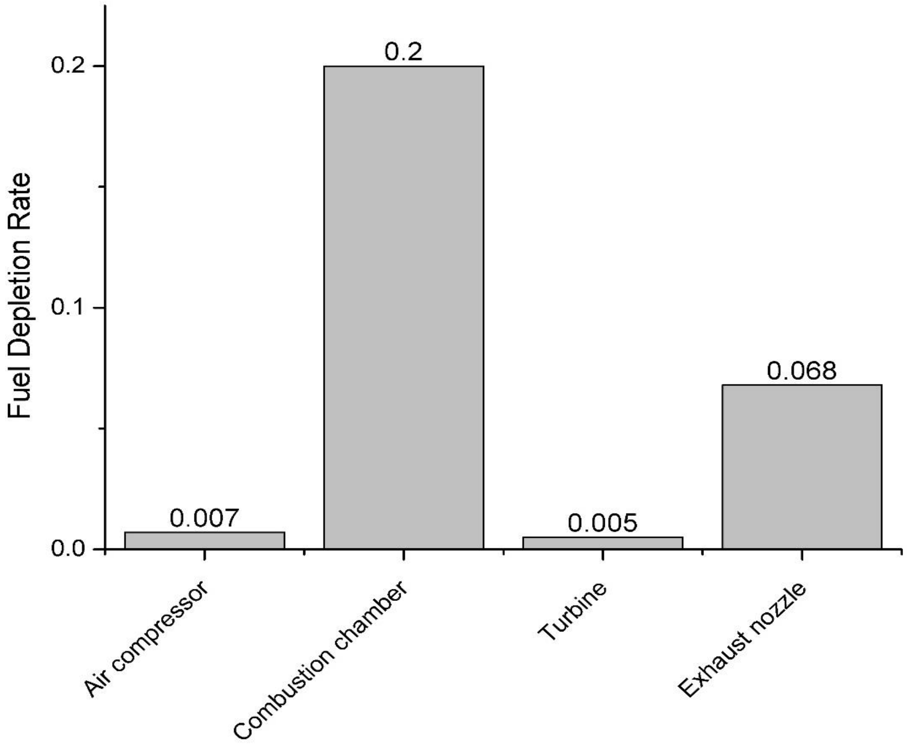

Figure 6. Fuel depletion rate of the simple gas turbine aero-engine components

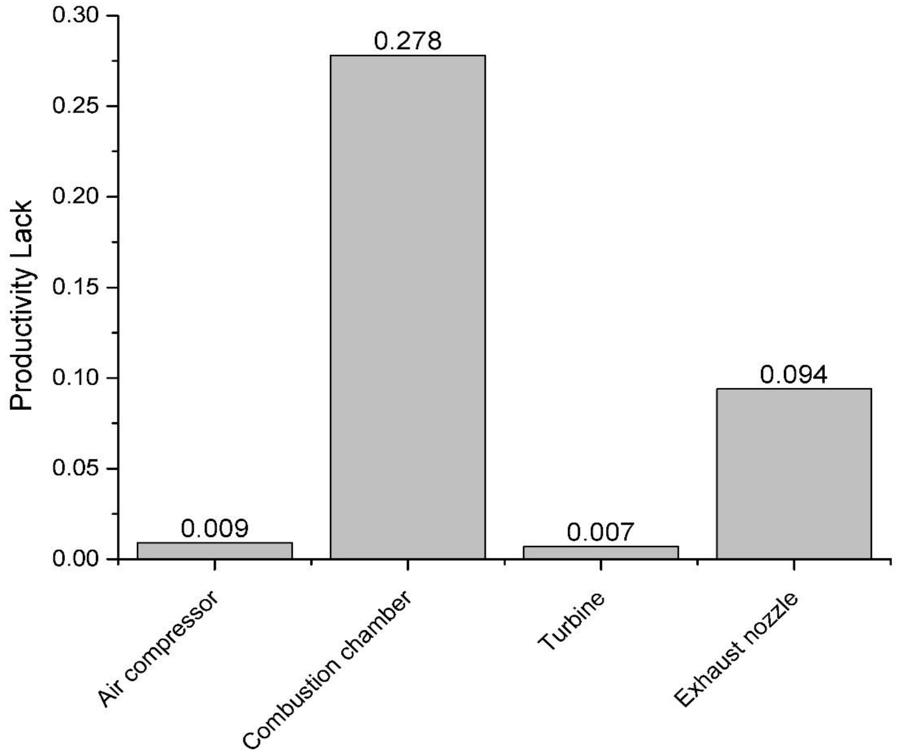

Figure 7. Productivity lack of the simple gas turbine aero-engine components

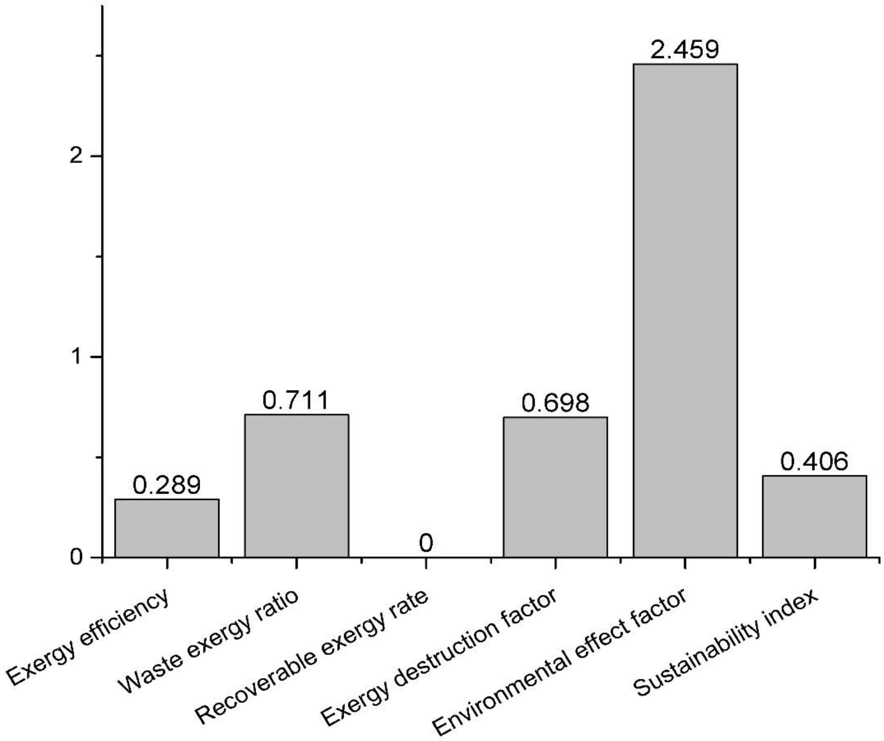

Figure 8. Sustainability indicators of the simple gas turbine aero-engine

Table 4. Sustainability index comparison of the two engines evaluated in the current study and Ref. [25]

Sustainability Index	Current Study	Ref. [25]
Exergy efficiency	0.289	0.272
Waste exergy ratio	0.711	0.975
Exergy destruction factor	0.698	0.546
Environmental effect factor	2.459	3.584
Sustainability index	0.406	0.279

Table 5. Major design parameters of the two engines evaluated in the current study and Ref. [25]

Design Parameter	Current Study	Ref. [25]
Compressor pressure ratio	8.00	3.90
Compressor isentropic efficiency	0.82	-
Combustion chamber pressure loss	0.03	0.06
Turbine inlet temperature	1200	1056
Turbine isentropic efficiency	0.89	-
Turbine pressure ratio	4.20	2.34

Table 4 presents the comparison of sustainability indexes of the evaluated engine in the current study with the sustainability indexes of the examined engine in Ref. [25]. The variation of the indexes are relatively small if they are compared. Characteristics and design parameters of two engines are different each other. Thus, that difference yields the state seen in Table 3. However the values of indexes are considered to be close if the characteristics of these engines are taken into account. In Table 5, design characteristics of both engines are summarized.

At the end of the analyses, the ecological function is calculated to be -8732.21 kW. This value, being under zero, means that the destructed exergy rate within the whole engine is more than the generated thrust. The main objective of a design, from an ecological perspective, is to maximize ecological function while minimizing exergy destruction. Therefore, it is essential to optimize and improve the design of the examined gas turbine aero-engine. The author strongly recommends that designers focus on the combustion chamber component for a more sustainable and ecological gas turbine aero-engine.

CONCLUSIONS

In this study, the performance and sustainability evaluation of a gas turbine engine is presented. At the end of the study, the following implications are concluded by the author:

- The combustion chamber of the engine among all the components is found to be the most irreversible component and is where the highest exergy destruction occurs.
- The most efficient component, regarding exergy analysis, is found to be the turbine.
- Possible improvements in chemical processes, as well as combustion reaction, may yield degradation of irreversibility and exergy destruction within the combustion chamber.
- It is possible to develop a more sustainable aero-engine by reducing exergy destruction through the engine. Improvement in chemical processes is therefore essential.
- Using exergy analysis at the design stage is now a well-accepted strategy after much research and introduction of the method. However, consideration of exergo-sustainability indicators and ecological function for design optimization is strongly recommended in order to achieve more efficient and sustainable designs.

Optimization, environmental and economic evaluations of the gas turbine aero-engine examined in the current paper are under consideration for future studies by the author.

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NOMENCLATURE

0	Dead state
$1, 2, \ldots$	Engine station numbers
CH	Chemical
c_p	Specific heat capacity under constant pressure [kJ.kg^{-1}.K^{-1}]
$dest$	Destruction
ECO	Ecological function
$\dot{Ex}$	Exergy rate [kW]
$\dot{ex}$	Specific exergy [kJ.kg^{-1}]
$\overline{ex}$	Specific exergy [kJ.kmol^{-1}]
f_{dest}	Exergy destruction factor
H/C	Hydrogen and carbon ratio
h	Specific enthalpy [kJ.kg^{-1}]
in	Inlet
$\dot{IP}$	Improvement potential rate [kW]
ke	Specific kinetic energy [kJ.kg^{-1}]
KN	Kinetic
LHV	Lower heating value [kJ]
$loss$	Loss
M	Molar mass [kg.kmol^{-1}]
$\dot{m}$	Mass flow rate [kg.s-1]
N	Mole fraction
out	outlet
P	Pressure [kPa]
pe	Specific potential energy [kJ.kg^{-1}]

PH	Physical
PT	Potential
$\dot{Q}$	Heat transfer rate [kW]
r_{eef}	Environmental effect factor
r_{re}	Recoverable exergy rate
r_{waste}	Waste exergy ratio
$\dot{S}_{gen}$	Entropy generation rate [kW.K^{-1}]
T	Temperature [K]
$\dot{W}$	Work rate or power [kW]
δ	Fuel depletion rate
ε	Exergy efficiency [%]
Θ	Sustainability index
ξ	Productivity lack
χ	Relative irreversibility

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