Ekserji Analiz Metoduyla Füzeler ve İnsansız Hava Araçları (UAV) Tasarlanmış Bir Turbojet Motorunun Maksimum Çalışma Performansının Doğrulanması

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(Alınış / Received: 16.01.2019, Kabul / Accepted: 09.02.2019, Online Yayınlanma/ Published Online: 30.04.2019)

Anahtar Kelimeler
Füzeler
İnsansız Hava Araçları
Turbojet Motoru
Exergy Analizi
Performans Parametreleri

Öz: Bu çalışma, füzeler ve insansız hava araçları için tasarlanan bir turbojet motorunun performans doğrulaması ekserji analiz metodu ile yapılmıştır. Bu araştırma için bazı ekserjetik performans doğrulama parametreleri geliştirilmiş ve kullanılmıştır. Bu parametreler, yeni geliştirilen motorun performans, sürdürülebilirlik ve çevresel etki seviyelerini belirlemek için motor tasarımcılarına yardımcı olacaktır. Maksimum çalışma şartları için incelenen turbojet motorunun ekserji verimi, iyileştirilmiş ekserji verimi, atık ekserji oranı, yakıt ekserjisi atık oranı, atık ekserji iyileştirme potansiyeli oranı, üretim kaybı oranı, yakıt ekserjisi iyileştirme potansiyeli oranı, atık ekserji maliyet akışı, çevresel etki faktörü, ekolojik etki faktörü, sürdürebilirlik indeksi ve sürdürülebilir verimlilik faktörü; sırasıyla %9.71, %52.55, %90.29, %90.29, %90.29, %929.54, %81.52, 32.29x10^{-3} kW/$, 9.295, 10.295, 0.108 ve 1.108 olarak hesaplanmıştır. Ekserjetik performans analiz sonuçları; motorun ekserji verimi arttırmak ve çevresel etkilerini azaltmak için tasarımcıların ve araştırmacıların kompresör ve yanma odasını iyileştirmeye odaklanmaları gerektiğini göstermiştir.

Maximum Operation Performance Evaluation of a Turbojet Engine Designed for Missiles and Unmanned Aerial Vehicles (UAV) with Exergy Analysis Methodology

Keywords
Missiles
Unmanned Aerial Vehicles
Turbojet Engine
Exergy Analysis
Performance Parameters

Abstract: In this study, performance evaluation of a turbojet engine designed for missiles and Unmanned Aerial Vehicles (UAV is done with exergy analysis methodology. Some exergetic performance assessment parameters are developed and used for this investigation. These parameters help the engine designers to determine the levels of performance, sustainability and environmental impact of the new designed engine. The exergy efficiency, the improved exergy efficiency, the waste exergy ratio, the fuel exergy waste ratio, the waste exergy improvement potential ratio, the productivity lack ratio, the fuel exergy improvement potential ratio, the waste exergy cost rate, the environmental effect factor, the ecological effect factor, exergetic sustainability index and sustainable efficiency factor are estimated to be 9.71%, 52.55%, 90.29%, 90.29%, 90.29%, 929.54%, 81.52%, 32.29x10^{-3} kW/$, 9.295, 10.295, 0.108 and 1.108 for the maximum operation mode of the investigated turbojet engine, respectively. The analyzing results of exergetic performance indicate that the designers and researchers shall focus on the improvement of engine compressor and combustor to progress the exergy efficiency of engine and to decrease the environmental impacts of engine.

1. Introduction

Aero-gas turbine engines can be used as power systems of various Unmanned Aerial Vehicles (UAV). These air vehicles are classified according to range, endurance, the altitude, flight speeds, and the sensor and payloads. Recently, interesting in small gas turbines has increased especially for remote control airplanes and the UAVs because of their extremely-high thrust-to weight ratio [1].

UAVs have various applications such as: agricultural purposes, photography, surveillance for enemy activity, pollution, sea-lane and coast line monitoring, herd driving and monitoring, coastguard applications, surveillance for illegal imports, fire services for forestry and detection, shadowing enemy vessels, decoying missiles by the emission of artificial signatures, reconnaissance, target designation and monitoring, land mines location and destruction [2].

UAV was the most dynamic growth sector of the world aerospace industry last decade. Annual global UAV expenditure is predicted to rise from its amount of about $6.4 billion in 2014 to $11.5 billion, totaling almost $91 billion in the next ten years. It is noticed that 20% increasing in UAV manufacturing companies for the year of 2013, 40% increasing in air vehicles just in between 2011 and 2013, reaching up to 57 countries, 270 companies, and more than 960 air vehicles in the year of 2013[3].

All of small turbojet engine manufacturers (Teledyne, Microturbo, Hamilton Sundstrand and Williams International) produce turbofan or turbojet engines in the low thrust range for missile and UAV programs. The microturbo TRI 40 turbojet engine is rated at between 2.50 to 3.40 KN. TRI 40 is currently designed and used for the target drones, anti-ship missiles, and remotely piloted vehicles at 6,000 m at up to Mach 0.95 with JP8 or JP10 jet fuel. The TRI 60-1 turbojet engine is rated at 3.5 kN maximum continuous and it powers anti-ship missile (BAE Sea Eagle, P.3T)with the name of TRI 60-1 067. Moreover, it also powers the Mirach 600 and Meteor SpAMirach 300. Another version, namely TRI 60-2, is a 3.7 kN thrust force and it is used for the Beech MQM-107B,Aerospatiale C.22 and Saab RBS15 anti-ship missiles, prototypes of some target drones (such as Hindustan Aeronautics Ltd (HAL) and Northrop NV-144/NV-151).

The TRI 60-3 is used in the Beech BQM-126 with 4.0kN thrust force. This engine model has also been selected to provide power for MQM-107Bs for the U.S. Air Force. The TRI 60-5 is an engine variant producing 4.4 kN. It was selected to power the Beech MQM-107B Streaker target drone. The TRI 60-30 is an application for the Matra SCALP/APACHE and U.K. Storm Shadow with 5.33 kN thrust force [4].

On the other hand, the Williams F107-WR-101, -400, and -402 turbofan engine equip the General Dynamics BGM-109 Tomahawk (ground-launched cruise missile), Boeing AGM-86B (air-launched cruise missile) and sea-launched cruise missile with 2.67 kN thrust force. The F107-WR-103 turbofan, formerly known as the F107-WR-14A6, is the production model designated for the remainder of the ALCM buy. It is rated at approximately 14.44 kN, and incorporates the use of new materials in the turbine section for a much higher turbine inlet temperature. The F107-WR-104 is a possible development of the original WR19, with a substantial up rating to over 5.33 kN. The F107-WR-105/401 model offers an increase in thrust to 6.22 kN; 10:1 or better thrust-to-weight. The engine could repower all operational Air-Launched, Sea-Launched, and Ground-Launched Cruise Missiles now employing the F107. The F112-WR-100 is the USAF designation for the F107-WR-103 engine that has been identified as the propulsion engine for the General Dynamics Corp (Convair Division) AGM-129 Advanced Cruise Missile. While this engine variant's thrust rating is classified, we know that it is in the 3.3-kN class. The F112 also powered the Douglas/NASA X-36 test drones. The F121-WR-100 is the smallest Williams International engine. It was designated for the air-launched version of the TACIT RAINBOW. For this application, the engine was rated at 0.66 kN. In 1999, a scaled-down version of the F122, USAF designation F415, was selected to power the Raytheon Tactical Tomahawk cruise missile after the Teledyne F402 turbojet was deselected [5].

Air transportation has come to measure its technical improvement in the increasing efficiency of its power systems. Therefore, specific fuel consumption is very important one of the considered things because of a relationship between environmental impact (due to decreasing fuel consumption reduces CO_2 emissions), energetic and fuel consumption performance. So, the most direct way to improve air vehicle fuel efficiency is used new latest available technology for aircrafts [6].

In the open literature, the studies about the performance assessment of aero-engines are classified as follows: (i) related to the performance evaluation: specific fuel consumption, specific thrust, efficiencies (propulsive, thermal and overall) [7-9], (ii) exergy analysis for turbojet [10-15], turbofan [16-18]and turboprop/shaft engines [19-21] (iii) indicating the effect of exergetic efficiency-reference altitude for aircraft engines [22-23], (iv) determining the exergoeconomic analysis methods [11, 21, 24-25], (v) analyzing the exergy and environmental performance of aircraft engines on the various flight phases [26-27], (vi) evaluating the exergo-sustainability performance of turboprop [24, 28], and (vii) assessing the environmental damage cost analysis of turboprop engine [24].

In a thermal system, thermodynamic inefficiencies and their magnitude, location and sources are identified with the aid of exergy analysis. Exergetic information is very useful for improving the energetic efficiency and cost effectiveness of a system to comparing the similar thermal systems.

A Stand of Missile (SOM) was developed by Roketsan for Turkish Army Forces. During the design, research and development studies, the Microturbo TRI40 turbojet engine was used on the SOM. Then, Roketsan took a decision that a new design turbojet engine is developed and used on the SOM [29, 30] .The main goals of the present study are given as follows:

- Evaluating exergetic performance of a new designed turbojet.
- Determining the component exergy destructions.
- Component-based suggesting according to improved, modified or replaced for the best results of increasing the overall exergy efficiency of the engine.

2. Investigated Turbojet Engine and Its Technical Data

The investigated turbojet engine was developed for powering up the Stand of Missile (SOM) and it will be planned to use on Unmanned Aerial Vehicle (UAV). The engine generates 3500 N thrust power at maximum operation mode under the sea level conditions. The information about the general system description of turbojet engine, assumptions made and the specific heat capacity of combustion gases are given in this section.

2.1. General System Description of a Medium-Scale Turbojet Engine (TJE)

The investigated medium scale turbojet engine (TJE) was designed for using on the air-to-air and air-to-land types missiles. Under the standard day-sea level conditions (i.e., T_o=288.15 K, P_o=101.325 kPa), the TJE has the following specifications [31]:

- Maximum thrust: 3500 N.
- Compressor pressure ratio: 5.5
- Mass flow of air: 8.66 kg/s.
- Mass flow of fuel: 0.1574 kg/s.
- Air to Fuel ratio: 50.02
- Pressure loss in the combustion chamber: 5%
- High pressure turbine inlet gas temperature: 1083.15 K.
- High pressure turbine outlet gas temperature: 921.15 K.
- High pressure turbine expansion ratio: 2.68
- Outlet temperature and pressure for exhaust: 918.65 K and 193.6 kPa.
- Manufacturer selling price: 200000 $.

For collecting the measurement data such as temperature, pressure and engine thrust; the thermocouples, the pressure transducers and the load cell were installed on the TJE engine as shown in Fig.1.

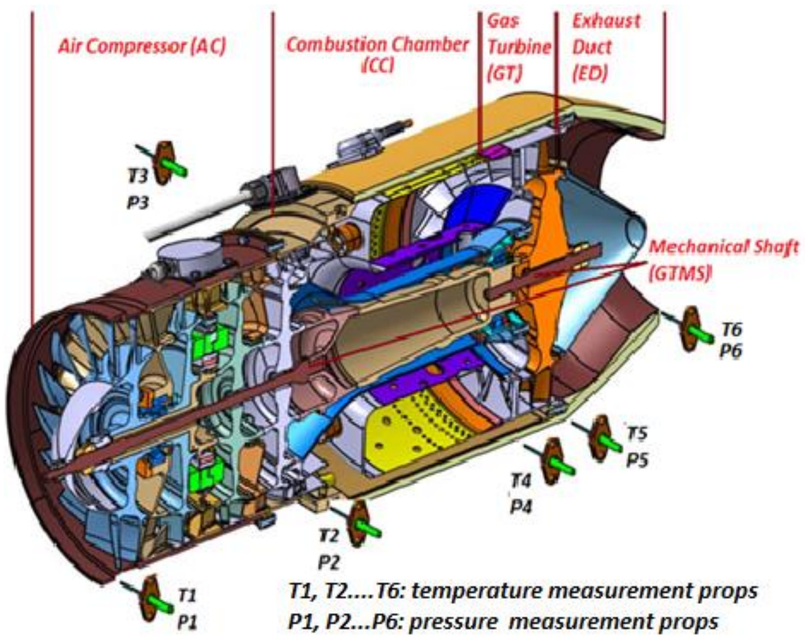

Fig.1. The cutaway of the turbojet engine (TJE) and measurement devices [31].

The engine thrust of the turbojet engine can be calculated from:

$$F = \dot{m}_{out}V_{out} - \dot{m}_{in}V_{in} + A_{out}P_{out} - A_{in}P_{in} \quad (1)$$

Due to the engine is operated in a ground test cell and/or a ground operation test, flight velocity $(V_{in} \cong 0)$ is assumed as zero. The velocity of exhaust gases is found to be 396.94 m/s from eqn. (1) for 3500 N-maximum engine thrust.

The simplified schematic of the TJE is given in Fig 2. The TJE engine's main components are compressor (AC), combustion chamber (CC), gas turbine (or high pressure turbine) (GT), exhaust duct (ED) and the gas turbine mechanical shaft (GTMS).

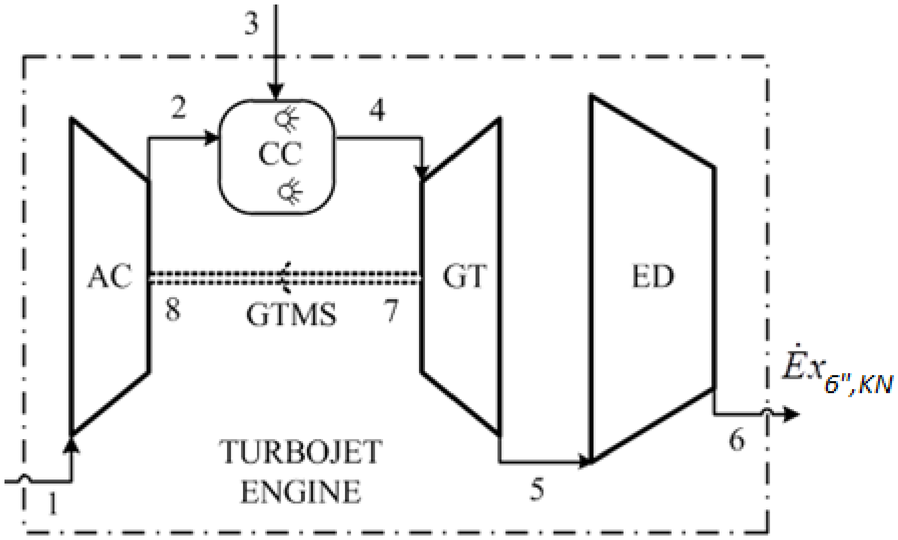

Fig.2. A simplified schematic of the investigated TJE.

2.2. Assumptions

In this study, the assumptions made are listed as below:

- The fuel injected to combustion chamber was the JP-8 jet fuel.
- The chemical formula of jet fuel was assumed as $C_{12}H_{23}$ and The LHV was to be 42800 kJ/kg.
- The velocity of air mass flow entering the engine was taken zero due to the static run tests.
- The changes in the kinetic energy, the kinetic exergy, the potential energy and the potential exergy within the engine were assumed to be negligible.
- The cooling air mass flow was not considered for the analysis.
- The engine operated in a steady-state and steady flow.
- The principle of ideal-gas mixture was applied for the air and combustion gaseous.
- The combustion reaction was complete.
- The compressor and the gas turbine considered as adiabatic.
- The temperature and the pressure of the ambient air state were taken to be 288.15 K and 101.33 kPa, respectively.

2.3. Specific Heat Capacity of Emission Gases and Air

For 50.02 air-to fuel ratio, the general combustion reaction equation is obtained as follows:

$$C_{12}H_{23} + 321.32\begin{pmatrix} 0.7448\,N_2 + \\ 0.2059\,O_2 + \\ 0.0003\,CO_2 + \\ 0.019\,H_2O \end{pmatrix} \rightarrow 12.096\,CO_2 + 17.605\,H_2O + 48.410\,O_2 + 248.959\,N_2 \quad (2)$$

After combustion reaction, the mass compositions of combustion gases are obtained to be 5.68% (0.500 kg/s) CO_2, 3.38% (0.298 kg/s) H_2O, 16.53% (1.455 kg/s) O_2 and 74.41% (6.552 kg/s) N_2. The universal gas constant (R_{gas}) of the emissions is estimated to be 0.29013kJ/kgK.

The air is composed of nitrogen 77.48%, oxygen 20.59%, carbon dioxide 0.03% and water vapor 1.90%. There are very small amount of argon, carbon monoxide, etc., in the air, which are neglected in this study. The pressured air mixed with fuel and burned in the combustion chamber to enable stable burning and the air-to-fuel ratio is to be at appropriate level. To have completed burning of fuel and to decrease the temperature, the air-to-fuel ratio in the combustion chamber is always higher than stoichiometric ratio. Because of this, there is a significant amount of oxygen within the combustion gases.

Based on mass rates of the emissions, the hot gases $c_{P,cg}$ value has been calculated in terms of temperature as shown in Eq. (3) by applying the $c_{P,cg}$ values of each emission [32];

$$c_{P,cg}(T) = 0.98853 + \frac{0.01176}{10^2}T + \frac{0.01523}{10^5}T^2 - \frac{0.06665}{10^9}T^3 \quad (3)$$

The ideal gas constant value of combustion gases was taken to be 0.2901 $kJ(kg-K)^{-1}$. The specific heat capacity of air is a function of temperature (in K) and it is determined from:

$$c_{P,a}(T) = 1.04841 - \left(\frac{3.83719\,T}{10^4}\right) + \left(\frac{9.45378\,T^2}{10^7}\right) - \left(\frac{5.49031\,T^3}{10^{10}}\right) + \left(\frac{7.92981\,T^4}{10^{14}}\right) \quad (4)$$

3. Exergy Analyzing Methodology

Exergy is a measure of the maximum work to be obtained from any system. Exergy analysis includes four variables as $\dot{E}x_F$ (fuel exergyrate), $\dot{E}x_{\Pr}$ (product exergy rate), $\dot{E}x_D$ (exergy destruction rate)and $\dot{E}x_L$ (exergy loss rate).

3.1. Basic Exergy Terms

Exergy waste is a measure of the irreversibility of a process, and that it is proportional to the increase in entropy and it can be evaluated by calculating the entropy increase. Exergetic analysis helps to determine the best theoretical performance of power systems and its components [33].

Exergy balance is given as follows for any control volume at steady state [34-35]:

$$\dot{E}x_F = \sum \dot{E}x_{in,,tot} = \dot{E}x_{\Pr} + \sum_{k=1}^{n} \dot{E}x_{D,k} + \dot{E}x_L \quad (5)$$

The total specific exergy for a flow of matter through a system can be formulated from [24] neglecting nuclear, magnetism, electricity and surface tension effects:

$$\varepsilon_{tot} = \varepsilon^{PH} + \varepsilon^{KN} + \varepsilon^{PT} + \varepsilon^{CH} \quad (6)$$

$$\dot{E}x_{tot} = \dot{m}\left(\varepsilon^{PH} + \varepsilon^{KN} + \varepsilon^{PT} + \varepsilon^{CH}\right) \quad (7)$$

The specific physical exergy for air and combustion gaseous may be written as [36-38]:

$$\varepsilon^{PH} = c_{P(T)}\left[T - T_o - T_o \ln\left(\frac{T}{T_o}\right)\right] + RT_o \ln\left(\frac{P}{P_o}\right) \quad (8)$$

The specific kinetic exergy of air and combustion gases is determined from [36-38]:

$$\varepsilon^{KN} = \frac{V^2}{2000} \tag{9}$$

The specific chemical exergy of fuel can be determined as follows [36-38]:

$$\varepsilon_F^{CH} = LHV\xi \tag{10}$$

Where the ξ denotes the liquid fuel exergy grade function. The ξ of liquid fuels $(C_a H_b)$ on a unit mass is obtained from [35-37]:

$$\xi \cong 1.04224 + 0.011925\,\frac{b}{a} - \frac{0.042}{a} \tag{11}$$

ξ is calculated to be 1.0616 for JP-8 jet fuel $(C_{12}H_{23})$.

3.2. Exergetic balance equations for engine and main components

The exergetic balance equations for the whole engine and its components can be written as:

For Air Compressor (AC):

$$\dot{E}x_{D,AC} = \dot{W}_8 - \left(\dot{E}x_2 - \dot{E}x_1\right) \tag{12}$$

For Combustion Chamber (CC):

$$\dot{E}x_{D,CC} = \dot{E}x_3 - \left(\dot{E}x_4 - \dot{E}x_2\right) \tag{13}$$

For Gas Turbine (GT):

$$\dot{E}x_{D,GT} = \left(\dot{E}x_4 - \dot{E}x_5\right) - \dot{W}_7 \tag{14}$$

For Exhaust Duct (ED):

$$\dot{E}x_{D,ED} = \dot{E}x_5 - \dot{E}x_6 \tag{15}$$

For Gas Turbine Mechanical Shaft (GTMS):

$$\dot{E}x_{D,GTMS} = \dot{W}_7 - \dot{W}_8 \tag{16}$$

For TJE engine;

$$\sum \dot{E}x_{D,TJE} = \dot{E}x_{D,AC} + \dot{E}x_{D,CC} + \dot{E}x_{D,GT} + \dot{E}x_{D,ED} + \dot{E}x_{D,GTMS} \tag{17}$$

On the other hand; total exergy losses from TJE are calculated as follows:

$$\sum \dot{E}x_{L,TJE} = \left(\dot{E}x_{1,KN} + \dot{E}x_{3,F}\right)_{TJE} - \dot{E}x_{6'',KN,TJE} - \sum \dot{E}x_{D,TJE} \tag{18}$$

Total waste exergy is calculated by:

$$\dot{E}x_{WE,TJE} = \sum \dot{E}x_{D,TJE} + \sum \dot{E}x_{L,TJE} \tag{19}$$

3.3. Exergetic performance metrics for engine components

Several exergetic performance metrics are developed and identified as the following.

- *Exergetic efficiency* (ψ)*:* The ψ of the k'th component is the ratio of product exergy to fuel exergy. It can be given as follows:

$$\psi_k = \frac{\dot{E}x_{\mathrm{Pr},k}}{\dot{E}x_{F,k}} = 1 - \frac{\dot{E}x_{D,k}}{\dot{E}x_{F,k}} \tag{20}$$

- *Relative exergy destruction ratio* (α)*:* The α is the ratio of the exergy destruction of to total exergy destruction within the system. It is accounted by:

$$\alpha_k = \frac{\dot{E}x_{D,k}}{\sum \dot{E}x_{D,TJE}} \tag{21}$$

- *Inlet exergy depletion ratio* (β)*:* The β is the ratio of the exergy destruction to the fuel exergy of the k'th component as given in Eq.22:

$$\beta_k = \frac{\dot{E}x_{D,k}}{\dot{E}x_{F,k}} \tag{22}$$

- *Fuel exergy depletion ratio* (χ)*:*The χ is the ratio of the exergy destruction of the fuel exergy. It is defined as follows:

$$\chi_k = \frac{\dot{E}x_{D,k}}{\dot{E}x_{3,F,TJE}} \quad (23)$$

- *Productivity lack ratio* (δ)*:* The δ is identified as the ratio of the exergy destruction to the product exergy of a system. It is given as follows:

$$\delta_k = \frac{\dot{E}x_{D,k}}{\dot{E}x_{6'',\mathrm{Pr},TFE}} \quad (24)$$

- *Product ratio indicator* (ϕ)*:* The ϕ is the ratio of product exergy rate to the product exergy and is given as follows:

$$\phi_k = \frac{\dot{E}x_{\mathrm{Pr},k}}{\dot{E}x_{6'',\mathrm{Pr},TJE}} \quad (25)$$

- *Fuel ratio indicator* (φ)*:* The φ is calculated by dividing the fuel exergy to the total fuel exergy and given as follows:

$$\varphi_k = \frac{\dot{E}x_{F,k}}{\dot{E}x_{3,F,TJE}} \quad (26)$$

- *Exergetic improvement potential (ExIP):* For the exergy consumption minimization, The maximum improvement can be achieved in the exergy efficiency for a power system. So, exergetic improvement potential (*ExIP)* must be defined. *ExIP* is written as follows:

$$\dot{E}xIP_k = (1-\psi_k)\dot{E}x_{D,k} \quad (27)$$

- *Relative exergetic improvement potential ratio* (γ)*:* The γ is the ratio of the exergetic improvement potential of k'th component to the total exergetic improvement potential of all components. The γ is calculated from:

$$\gamma_k = \frac{\dot{E}xIP_k}{\sum_{k=1}^{n}\dot{E}xIP_k} \text{ (n= number of components)} \quad (28)$$

- *Exergy destruction improvement ratio* (λ): The λ is the ratio of the exergetic improvement potential of k'th component to the exergy destruction rate of k'th component. High value of exergetic destruction improvement ratio demonstrates that exergetic improvement potential rate for a component occurs in high level. The λ is calculated from:

$$\lambda_k = \frac{\dot{E}xIP_k}{\dot{E}x_{D,k}} \quad (29)$$

- *Component inlet exergy improvement potential ratio* (μ): The μ iscalculated by dividing the exergetic improvement potential rate of k'th component to the sum of the inlet flows as fuel exergy into the k'th component. It is estimated by:

$$\mu_k = \frac{\dot{E}xIP_k}{\dot{E}x_{F,k}} \quad (30)$$

- *Fuel exergy improvement potential ratio* (ν): The ν is the ratio of the exergetic improvement potential rate ofk'th component to the total fuel exergy of the system. It is found by:

$$\nu_k = \frac{\dot{E}xIP_k}{\dot{E}x_{3,F,TJE}} \quad (31)$$

- *Improved exergetic efficiency* (Ψ): If an exergetic improvement is realized in a component, the fuel exergy rate required for a component decreases for constant production and the exergy efficiency of the component increases. This new value of exergetic efficiency can be named as the improved exergetic efficiency. The Ψ is calculated as follows:

$$\Psi_k = \frac{\dot{E}x_{\mathrm{Pr},k}}{\dot{E}x_{F,k} - \dot{E}xIP_k} \tag{32}$$

- *Exergy destruction cost rate* (π)*:* Exergy consumption creates an extra monetary lost during a production. A system with lower exergy consumption has more useful product exergy and subsequently more potential to do work. A less efficient system has low useful product exergy and less potential to do work. The loss in production potential can be represented as a cost rate. The π is the ratio of the exergy destruction rate of k'th component to the selling price of the system. It can be taken from:

$$\pi_k = \frac{\dot{E}x_{D,k}}{SP_{TJE}} \tag{33}$$

- *Relative exergy destruction cost rate* (ϖ)*:* The ϖ is the ratio of the exergy destruction cost rate of k'th component to the total exergy destruction cost rate within the system. This parameter indicates that which component of the system is more effective in the exergy destruction cost rate. The ϖ is estimated by:

$$\varpi_k = \frac{ExDCR_k}{\sum_{k=1..n} ExDCR} \tag{34}$$

- *Environmental effect factor (EEF):* One of the sustainability indicators is the environmental effect factor which is calculated the ratio of inlet exergy destruction ratio to the exergy efficiency. Environmental impact factor indicates whether or not it damages the environment because of its unusable waste exergy output and exergy destruction. The *EEF* can be counted by;

$$EEF_k = \frac{\beta_k}{\psi_k} \tag{35}$$

- *Exergetic sustainability index (ExSI)*: Its function of environmental effect factor can be found out by ratio of 1 to the environmental effect factor. The range of this index is between 0 and ∞. The higher efficiency means low exergy destruction ratio and low environmental effect factor as a result higher exergetic sustainability index. Measures to increase exergy efficiency can reduce environmental impact by reducing energy losses. Within the scope of exergy methods, such activities lead to increased exergy efficiency and reduced exergy consumption. The *ExSI* is figured out from:

$$ExSI_k = \frac{1}{EEF_k} \tag{36}$$

- *Sustainable efficiency factor (SEF):* If a process or system uses low amount fuel or energy for the desired production, it is said that this process or system has high exergetic efficiency value as well as high sustainability level because low emissions are emitted to the environment. An increasing in the exergetic efficiency results a rising in the sustainability level of the system. Consequently, the sustainable efficiency factor can be used as a sustainability assessment parameter and the *SEF* is picked up as follows;

$$SEF_k = \frac{1}{1-\psi_k} \tag{37}$$

- *Ecological effect factor (EcoEF):* The $EcoEF$ of the k'th component is estimated from following equation;

$$EcoEF_k = \frac{\dot{E}x_{F,k}}{\dot{E}x_{\mathrm{Pr},k}} = \frac{1}{\psi_k} \tag{38}$$

3.4. Exergetic performance metrics for whole engine

For whole engine the exergetic performance parameters can be written as following.

- *Exergetic efficiency* (ψ)*:* The ψ of the system is calculated by the ratio of the thrust power exergy rate to the sum of the inlet flows as fuel exergy. It can be estimated as follows:

$$\psi_{TJE} = \frac{\dot{E}x_{6",\mathrm{Pr}}}{\left(\dot{E}x_1 + \dot{E}x_3\right)} = 1 - \frac{\sum \dot{E}x_{WE,TJE}}{\left(\dot{E}x_1 + \dot{E}x_3\right)} \tag{39}$$

- *Waste exergyratio* (X)*:*The X is found out from the ratio of total waste exergy rate to sum of the inlet flows as fuel exergy as follows:

$$\mathrm{X}_{TJE} = \frac{\dot{E}x_{WE,TJE}}{\left(\dot{E}x_1 + \dot{E}x_3\right)_{TJE}} \tag{40}$$

- *Fuel exergy waste ratio* (Δ)*:* The Δ is counted from the ratio of total waste exergy rate to the fuel exergy rate of system by following equation:

$$\Delta_{TJE} = \frac{\dot{E}x_{WE,TJE}}{\dot{E}x_{3,TJE}} \tag{41}$$

- *Productivity lack ratio factor* (Φ)*:* The Φ is identified as the ratio of total waste exergy rate to total thrust power exergy rate of system. It is assessed by:

$$\Phi_{TJE} = \frac{\dot{E}x_{WE,TJE}}{\dot{E}x_{6",\mathrm{Pr},TJE}} \tag{42}$$

- *Exergetic improvement potential* $(\dot{E}xIP)$*:* The $\dot{E}xIP_{TJE}$ expresses that how much the waste exergy rate is recovered by improving the exergy efficiency of the system. It is taken from:

$$\dot{E}xIP_{TJE} = (1-\psi_{TJE})\dot{E}x_{WE,TJE} \tag{43}$$

- *Waste exergy improvement potential ratio* (Γ): The Γ is the ratio of exergetic improvement potential rate of the system to waste exergy rate of the system. It is estimated from:

$$\Gamma_{TJE} = \frac{\dot{E}xIP_{TJE}}{\dot{E}x_{WE,TJE}} \tag{44}$$

- *Fuel exergy improvement potential ratio* (Π): The Π is the ratio of exergetic improvement potential rate of system to fuel exergy rate of the system. It is calculated by:

$$\Pi_{TJE} = \frac{\dot{E}xIP_{TJE}}{\dot{E}x_{3,TJE}} \tag{45}$$

- *Improved exergetic efficiency* (Ψ): In accordance with the exergetic improvement potential rate that is realized within the system, the inlet exergy rate incoming to the system can be decreased and the exergy efficiency of the system can be increased. The Ψ_{TJE} is obtained from the following equation:

$$\Psi_{TFE} = \frac{\dot{E}x_{6",TJE}}{\left(\dot{E}x_1 + \dot{E}x_3 - \dot{E}xIP_{TJE}\right)} \tag{46}$$

- *Waste exergy cost rate* (Θ)*:* The Θ is explained as the ratio of waste exergy rate of system to system sellingprice. It is obtained from:

$$\Theta_{TJE} = \frac{\dot{E}x_{WE,TJE}}{SP_{TJE}} \tag{47}$$

- *Environmental effect factor* (EEF)*:* The EEF is described as the ratio of waste exergy ratio of system to the exergetic efficiency of system. It is computed by:

$$EEF_{TJE} = \frac{\mathrm{X}_{TJE}}{\psi_{TJE}} \tag{48}$$

- *Exergetic sustainability index* $(\dot{E}xSI)$: To calculate the $\dot{E}xSI$ of the system, it is applied the following equation:

$$ExSI_{TJE}=\frac{1}{EEF_{TJE}} \tag{49}$$

- *Sustainable efficiency factor (SEF):* The SEF of the system is derived from:

$$SEF_{TJE}=\frac{1}{1-\psi_{TJE}} \tag{50}$$

- *Ecological effect factor* $(EcoEF)$*:* The $EcoEF$ of the system is estimated from following equation:

$$EcoEF_{TJE}=\frac{\dot{E}x_{3,TJE}}{\dot{E}x_{6'',\mathrm{Pr},TJE}}=\frac{1}{\psi_{TJE}} \tag{51}$$

4. Results and Discussions

In the current study, exergy analysis of a new design turbojet engine (TJE) used on missiles is evaluated. The product exergy (kinetic exergy rate of exhaust gases) of the engine is calculated to be 694.65 kW from eqn. (9) while the velocity of exhaust gases is found to be 396.94 m/s from eqn. (1). For 7151.7 kW- fuel exergy rate and 694.65 kW-product exergy rate at the maximum engine power operation, condition, the exergy efficiency of the engine is determined to be 9.71%. However, the temperature, pressure, mass flow, specific heat capacity and exergy rate at the TJE's stations numbered in Fig.2 for maximum operation mode are given in Table 1.

Table 1. The exergy rate and other thermodynamic properties of the TJE at maximum operation mode.

State no.	*Fluid type/work*	*Pressure* $P(kPa)$	*Temperature* $T(K)$	*Mass flow rate* $\dot{m}(kgs^{-1})$	*Specific heat capacity* $c_P\ (kJ(kg-K)^{-1})$	*Exergy rate* $\dot{E}x\ (kW)$
0	Air	101.33	288.15	0.000	1.00375	0.00
1	Air	101.33	288.15	8.66	1.00375	0.00
2	Air	557.29	503.25	8.66	1.02984	1706.29
3	Fuel	220.63	298.15	0.1574		7151.70
4	Combustion gases	529.42	1083.15	8.8174	1.20989	5629.53
5	Combustion gases	197.55	921.15	8.8174	1.17382	3577.80
6	Combustion gases	191.62	916.54	8.8174	1.17294	3520.33
7	Mechanical power					2021.22
8	Mechanical power					1983.46
6"	Kinetic energy/exergy					694.65

4.1. Exergetic performance results of engine components

As a result of the exergy analysis, the exergetic parameters for each component of the engine are presented in Tables 2-4 in addition to main exergy parameters.

Table 2. Exergy rate, exergetic efficiency and exergetic performance metrics of the engine components at maximum operation mode

Components	$\dot{E}x_F$ (kW)	$\dot{E}x_{\mathrm{Pr}}$ (kW)	$\dot{E}x_D$ (kW)	ψ (%)	α (%)	β (%)	χ (%)	δ (%)	ϕ (%)	φ (%)
AC	1983.46	1706.29	277.18	86.026	7.633	13.974	3.876	39.902	245.633	27.734
CC	8857.99	5629.53	3228.46	63.553	88.905	36.447	45.143	464.761	810.412	123.859
GT	2051.73	2021.22	30.51	98.513	0.840	1.487	0.427	4.392	290.970	28.689
GTMS	2021.22	1983.46	37.76	98.132	1.040	1.868	0.528	5.435	285.534	28.262
ED	3577.80	3520.33	57.47	98.394	1.583	1.606	0.804	8.274	506.777	50.027

Table 3. Exergy rate, exergetic improvement potential and exergetic performance metrics of the engine components at maximum operation mode

Components	$\dot{E}x_F$ (kW)	$\dot{E}x_{Pr}$ (kW)	$\dot{E}x_D$ (kW)	$\dot{E}xIP$ (kW)	γ (%)	λ (%)	μ (%)	ν (%)	Ψ (%)
AC	1983.46	1706.29	277.18	38.734	3.181	13.974	1.953	0.542	87.739
CC	8857.99	5629.53	3228.46	1176.67	96.648	36.447	13.284	16.453	73.289
GT	2051.73	2021.22	30.51	0.454	0.037	1.487	0.022	0.006	98.535
GTMS	2021.22	1983.46	37.76	0.705	0.058	1.868	0.035	0.010	98.166
ED	3577.80	3520.33	57.47	0.923	0.076	1.606	0.026	0.013	98.419

Table 4. Exergy rate, exergy destruction cost rate and exergetic environmental performance metrics of the engine components at maximum operation mode

Components	$\dot{E}x_F$ (kW)	$\dot{E}x_{Pr}$ (kW)	$\dot{E}x_D$ (kW)	π $(10^{-3} kW/\$)$	ϖ (%)	*EEF* (-)	*ExSI* (-)	*SEF* (-)	*EcoEF* (-)
AC	1983.46	1706.29	277.18	1.386	7.633	0.162	6.156	7.156	1.162
CC	8857.99	5629.53	3228.46	16.142	88.905	0.573	1.744	2.744	1.573
GT	2051.73	2021.22	30.51	0.153	0.840	0.015	66.250	67.250	1.015
GTMS	2021.22	1983.46	37.76	0.189	1.040	0.019	52.534	53.534	1.019
ED	3577.80	3520.33	57.47	0.287	1.583	0.016	61.253	62.253	1.016

The main findings of the exergy analysis are summarized as follows:

- The real exergetic efficiency (ψ) values of the AC, CC, GT, GTMS and ED are calculated to be 86.03%, 63.55%, 98.51%, 98.13% and 98.39%, respectively. On the other hand, the improved exergy efficiency (Ψ) values of the AC, CC, GT, GTMS and ED are obtained to be 87.74%, 73.29%, 98.53%, 98.17% and 98.42%, respectively. The real and improved exergy efficiency values of the engine components are illustrated in Fig.3. Fig.3 indicates that the CC has the maximum improvement potential with 9.74% increasing in the exergy efficiency.

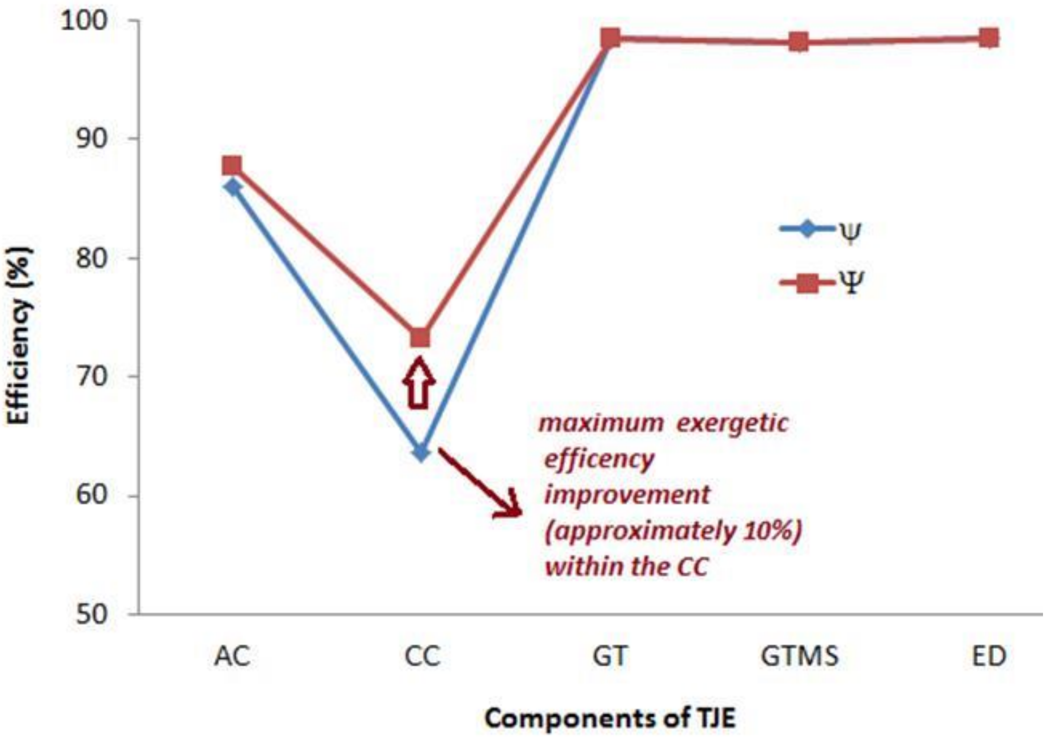

Fig.3. The real and improved exergy efficiency values of TJE's components.

- Between the components, the CC has the maximum exergy destruction rate with 3228.46 kW that is generates 88.90% of the total exergy destruction rate (3631.37 kW) within the engine. Because of this reason, the maximum values of the relative exergy destruction (α), the inlet exergy depletion ratio (β), the fuel exergy depletion ratio (χ), the productivity lack ratio (δ), the product ratio indicator (ϕ) and the fuel ratio indicator (φ) take place in the CC component with 88.90%, 36.45%, 45.14%, 464.76%, 810.41% and 123.86%, respectively.
- The CC has the maximum exergetic improvement potential $(\dot{E}xIP)$ with 1176.67 kW hence it is the lowest exergy efficiency between the components. Furthermore, the CC owns the maximum values of the relative exergy improvement potential (γ), the exergy destruction improvement ratio (λ), the component inlet exergy improvement potential ratio (μ) and fuel exergy improvement potential ratio (ν) with 96.65%, 36.45%, 13.28% and 16.45%, respectively.
- The exergy destruction produces the cost rate because this portion of exergy rate is not converted to the desired product. The CC generates the maximum exergy destruction cost rate (π) with 16.14x10^{-3} kW/$ between the components. Besides, the CC has the maximum relative cost rate ratio (ϖ) with 88.91%.
- When the environmental and sustainability indicators are examined for the engine components; the environmental effect factor (EEF), exergetic sustainability index $(ExSI)$, sustainable efficiency factor (SEF) and ecological effect factor $(EcoEF)$ are realized the maximum in the CC with 0.573, 1.744, 2.744 and 1.573, respectively.

The above-mentioned results clearly indicate that the CC has bed exergetic, environmental and sustainability performance metrics due to the combustion irreversibilities. Combustion of the fuel is a very complex phenomenon and it is highly thermodynamically irreversible process and limits the conversion of the fuel energy into the useful energy [39-40].

4.2. Exergetic performance metrics of whole engine

The exergy rate flows of the engine are 7151.7 kW-fuel exergy rate $(\dot{E}x_{3,F})$, 694.65 kW-product exergy rate $(\dot{E}x_{6'',KN})$, 3631.37 kW-total exergy destruction rate $(\sum \dot{E}x_D)$ and 2685.68 kW- exergy losses rate $(\dot{E}x_L)$. The distribution of the fuel exergy inletting the engine is shown in Fig. 4. Fig.4 points out that the total exergy destruction rate is composed of 50.78% of fuel exergy rate while the exergy losses rate comprises 39.51% of fuel exergy rate. The exergetic performance parameters of whole engine are given in Table 5.

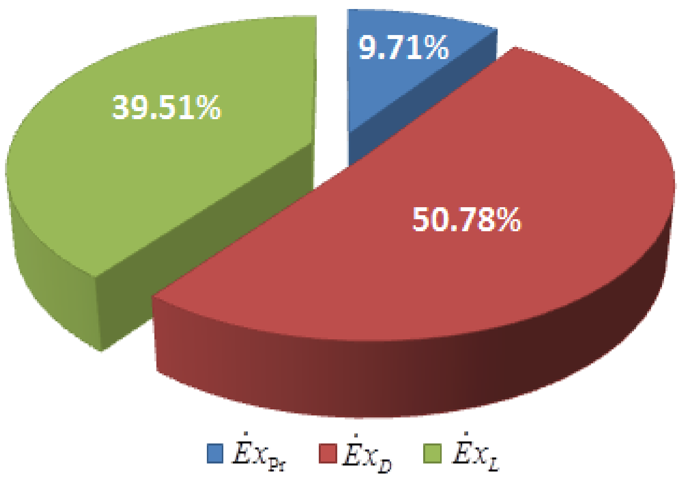

Fig. 4. Dividing the fuel exergy rate of the TJE into product exergy rate, exergy destruction rate and exergy losses rate.

Table 5. Exergy rate, exergetic efficiency and exergetic performance metrics of the whole engine at maximum operation mode

Parameters	Value	Parameters	Value	Parameters	Value
$\dot{E}x_F(kW)$	7151.70	Χ(%)	90.29	Ψ(%)	52.55
$\dot{E}x_{Pr}(kW)$	694.65	Δ(%)	90.29	$\Theta\left(10^{-3}kW/\$\right)$	32.29
$\dot{E}x_D(kW)$	3631.37	Φ(%)	929.54	*EEF*(-)	9.30
$\dot{E}x_L(kW)$	2825.68	$\dot{E}xIP(kW)$	5829.88	*ExSI*(-)	0.11
$\dot{E}x_{WE}(kW)$	6457.05	Γ(%)	90.29	*SEF*(-)	1.11
ψ (%)	9.71	Π(%)	81.52	*EcoEF*(-)	10.30

The main results of the exergetic analysis of whole engine are outlined as follows:

- The real exergy efficiency (ψ) of the TJE is calculated to be 9.71% while the waste exergy rate $\left(\dot{E}x_{WE}\right)$ is determined to be 6457.05 kW. If the necessary modification and improvements are realized on the engine, the 5829.88 kW-exergetic improvement potential rate $\left(\dot{E}xIP\right)$ of 6457.05 kW-waste exergy rates can be regained theoretically. In this situation, the exergy efficiency of engine that named as the improved exergy efficiency (Ψ) is estimated to be 52.55%.
- The waste exergy ratio (X), the fuel exergy waste ratio (Δ) and the waste exergy improvement potential ratio (Γ) are determined to be 90.29%.
- The productivity lack ratio (Φ), the fuel exergy improvement potential ratio (Π) and the waste exergy cost rate (Θ) are obtained to be 929.54%, 81.52% and 32.29x10^{-3} kW/$, respectively.
- On the other hand, when the environmental and sustainability indicators are examined for the whole engine; the environmental effect factor (EEF), exergetic sustainability index $(ExSI)$, sustainable efficiency factor (SEF) and ecological effect factor $(EcoEF)$ of the whole engine are determined to be 9.295, 0.108, 1.108 and 10.295, respectively. The results of environmental and sustainability metrics indicate that the engine exergy efficiency must advance the acceptable level between 20% and 30%. Particularly, the designers and researchers must focus on to improve the exergy efficiency of the CC component.

4.3. Comparing engine exergy efficiency performance with other investigated engines

The exergy efficiency values of new turbojet engine and other engines investigated in the previous studies are listed in Table 6. The exergy efficiency values of turbojet, turboprop and turbofan engines in the previous studies were estimated to be between 16.63% and 48.05% while the exergy efficiency of the new designed turbojet engine in this study is calculated to be 9.71%. When microjet engines are only taken into consideration, it is easily seen from Table 6 that the TRS18 micro turbojet is the highest exergy efficiency value with 48.05% [50]. This result indicates that the exergy efficiency of the engine, compared with other engines, is very low level. The designers and researchers must focus on the air compressor (AC) and combustion chamber (CC) to progress the engine exergy efficiency from 9.71% to the acceptable level between 20% and 30%.

Table 6. Comparing exergetic efficiency value of new engine with other engines.

Researcher	Investigated date	Engine Type	Exergy efficiency (%)
Aydin et al. [6]	2015	Turbofan	31.50
Balli [10]	2014	Turbojet	29.87
Balli et al. [11]	2008	Turbojet	34.84
Ehyaei et al. [15]	2013	Turbojet	25.60
Balli and Hepbasli [19]	2013	Turboprop	23.80
Aydın et al. [21]	2012	Turboprop	30.00
Etele and Rosen [22]	2001	Turbojet	16.9
Aydın et al. [28]	2013	Turboprop	29.20
Balli [35]	2017	Turbofan	25.70
Balli [36]	2017	Turboprop	16.63
Balli [37]	2017	Turbojet	39.41
Balli [41]	2017	Turbofan	26.80
Sohret et al. [42]	2016	Turboprop	26.74
Bastani et al. [43]	2015	Turbofan	44.00
Sohret et al. [44]	2017	Micro turbojet	27.25
Struchtrup and Elfring [45]	2008	Turbofan	34.80
Balli [46]	2017	Turbofan	19.92
Balli et al [47]	2017	Turbojet	26.39
Balli et al [48]	2017	Turboprop	17.24
Balli et al. [49]	2017	Micro turbojet	17.02
Aydin et al. [50]	2018	TRS18 micro turbojet	42.00
Balli [51]	2019	Turbofan	48.05
Present study		Turbojet	***9.71***

5. Conclusion

This study presents some developed exergetic assessment parameters to analyze and evaluate the medium-scale turbojet engine designed for using on Missiles. These parameters help the engine designers to measure the level of engine performance, the environmental impacts of the engine and its sustainability.

The exergy efficiency, the improved exergy efficiency, the waste exergy ratio, the fuel exergy waste ratio, the waste exergy improvement potential ratio,the productivity lack ratio, the fuel exergy improvement potential ratio, the waste exergy cost rate, the environmental effect factor, the ecological effect factor, exergetic sustainability index and sustainable efficiency factor are estimated to be 9.71% 52.55%, 90.29%, 90.29%, 90.29%, 929.54%, 81.52%, 32.29×10^{-3} kW/$, 9.295, 10.295, 0.108 and 1.108 for the maximum operation mode of the engine. The results of exergetic, environmental and sustainability metrics indicate that the designers and researchers must focus on the air compressor (AC) and combustion chamber (CC) to progress the engine exergy efficiency from 9.71% to the acceptable level between 20% and 30%.

The recommended exergetic assessment metrics in this study can be beneficial to analyze the similar systems as the turbojet, the turboprop and the turbofan engines.

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Nomenclature

A area (m^2)

AC air compressor

CC Combustion chamber

c_P specific heat capacity (kJ/kg.K)

$EcoEF$ ecological effect factor (-)

ED exhaust duct

EEF environmental effect factor (-)

ET engine thrust (N, kN)

$\dot{E}x$ exergy rate (kW)

$\dot{E}xIP$ exergetic improvement potential (kW)

ESI exergetic sustainability index (-)

GT gas turbine

$GTMS$ gas turbine mechanical shaft

LHV lower heating value of fuel ($kJkg^{-1}$)

$\dot{m}$ mass flow rate (kg/s, kg/h)

P pressure (kPa)

R universal gas constant($kJ\ kg^{-1}K^{-1}$)

SEF sustainable efficiency factor (-)

T temperature (K)

TJE turbojet engine

V velocity (m/s)

$\dot{W}$ work rate or power rate(KW)

Greek Letters

α relative exergy destruction ratio (%)

β inlet exergy depletion ratio (%)

χ fuel exergy depletion ratio (%)

δ productivity lack ratio (%)

ε specific exergy (kJ/kg)

ϕ product ratio indicator(%)

φ fuel ratio indicator(%)

γ relative exergetic improvement potential ratio(%)

λ exergy destruction improvement ratio(%)

μ component inlet exergy improvement potential ratio(%)

ν fuel exergy improvement potential ratio(%)

π exergy destruction cost rate (kW/$)

ϖ relative exergy destruction cost rate (-)

ξ fuel exery grade function (-)

ψ exergetic efficiency (%)

X waste exery ratio (%)

Δ fuel exergy waste ratio (%)

Φ productivity lack ratio factor (%)

Γ waste exergy improvement potential ratio(%)

Π fuel exergy improvement potential ratio(%)

Θ waste exergy cost rate(kW/$)

Ψ improvedexergetic efficiency (%)

Subscripts

A air

AC air compressor

CC combustion chamber

Cg combustion gases

CH chemical

D destruction

ED exhaust duct

F inlet streams as a fuel

GT Gas turbine

GTMS gas turbine mechanical shaft

In input

K k'th component

KN kinetic

L losses

Out output

P pressure

PH physical

Pr product

PT potential

T temperature

TJE turbojet engine

Tot total

WE waste exergy

0 dead state

Superscripts

CH	chemical
KN	kinetic
PH	physical
PT	potential