JAR - 2 / 2 E-ISSN: 2687-3338 AUGUST 2020

JOURNAL OF AVIATION RESEARCH

HAVACILIK ARAŞTIRMALARI DERGİSİ

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İSTANBUL - 2020

JOURNAL OF
AVIATION RESEARCH
HAVACILIK ARAŞTIRMALARI DERGİSİ

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This is a scholarly, international, peer-reviewed, open-access journal published international journal published twice a year.

Cilt: 2
Sayı: 2
Yıl: 2020

Volume: 2
Issue: 2
Year: 2020

2019 yılından itibaren yayımlanmaktadır.

Published since 2019.

Elektronik ortamda da yayınlanmaktadır:
https://dergipark.org.tr/jar
Ulaşmak için tarayınız:

This journal is also published digitally.
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JOURNAL OF AVIATION RESEARCH
HAVACILIK ARAŞTIRMALARI DERGİSİ

Journal of Aviation Research
Cilt/Vol: 2, Sayı/Issue 2
Ağustos/August, 2020
E-ISSN: 2687-3338
Published by Maltepe University
URL:
http://www.dergipark.gov.tr/jar

General Aviation and Thermodynamic Performance Analyses of Micro Turbojet Engine Used on Drones and Unmanned Aerial Vehicles (UAV)

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Araştırma Makalesi	**DOI:**	
Gönderi Tarihi: 25.04.2020	Kabul Tarihi: 17.05.2020	Online Yayın Tarihi: 31.08.2020

Abstract

The general aviation, energetic and exergetic performance analyses of a micro turbojet engine (MTJE) used on drones and UAVs and its major subcomponents are made for different operation modes (Mode-1,-2,-3,-4) in detail. Used performance metrics in this study help to measure the system performance level and to develop the system and its subsystems. The results indicate that the MTJE has the best performance values at the maximum operation modes (Mode-4) because the military engines, especially turbojet engine, are designed to be the most efficient in the maximum operation/take-off modes. The MTJE has the maximum energy efficiency via 19.190% at Mode-4 when it has the maximum exergy efficiency by 18.079% at Mode-4, respectively. Between the components, the combustion chamber has the lowest exergy efficiency values, the lowest sustainable efficiency factors, the highest exergy destruction rates, the highest exergetic improvement potential rates, the highest fuel exergy waste ratios and the highest productivity lack ratios for all operation modes. When the exergetic performance parameters are taken into consideration, the bad factor for the system is the combustion chamber by far. Therefore, all exergetic performance indicators show that the system owners and researchers focus on the components of the compressor and combustion chamber to improve the exergetic efficiency values of these components.

Keywords: Micro turbo jet engine, aviation, energy, exergy
JEL Classification: L93

Dronlar ve İnsansız Hava Araçlarında (UAV) Kullanılan Mikro Turbojet Motorunun Genel Havacılık ve Termodinamik Performans Analizi

Öz

Farklı çalışma modları (Mode-1,-2,-3,-4) için Dronlar ve UAV'lerde kullanılan bir mikro turbojet motorunun (MTJE) ve motorun alt sistemlerinin genel havacılık, enerji ve ekserji performans analizleri detaylı bir şekilde yapılmıştır. Bu çalışmada kullanılan performans ölçütleri; sistem performans seviyesinin ölçülmesine, sistem ve alt sistemlerinin geliştirilmesine yardımcı olacaktır. Sonuçlar; askeri motorların, özellikle turbojet motorlarının, maksimum çalışma/kalkış modunda en verimli olacak şekilde tasarlanmış olduğundan MTJE'nin en iyi performans değerlerine maksimum çalışma modunda (Mode-4) sahip olduğunu

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göstermektedir. MTJE motoru Mode-4 çalışma modunda; %18,08 ile maksimum ekserji verimine ve %19,19 ile maksimum enerji verimine sahiptir. Komponentler arasında yanma odası; tüm çalışma modları için en düşük ekserji verimlerine ve sürdürülebilir verim faktörlerine, en yüksek ekserji yıkım akışlarına, ekserji iyileştirme potansiyeli akışlarına, yakıt ekserjisi atık oranlarına ve üretebilirlik kayıp oranlarına sahiptir. Ekserji performans parametreleri dikkate alındığında, açık arayla sistem için kötü faktöryanma odasıdır. Bu nedenle, tüm ekserji performans göstergeleri; sistem sahiplerinin ve araştırmacıların kompresör ve yanma odası komponentlerinin ekserji verim değerlerini iyileştirmek amacıyla bu komponentler üzerinde odaklanmaları gerektiğini göstermektedir.

Anahtar kelimeler: Mikro turbojet motoru, havacılık, enerji, ekserji.
JEL Sınıflandırma: L93

INTRODUCTION

Aviation plays a key role in economic improvement and daily life. It contributes to our quality of life by enabling the movement of people and products all over the globe quickly and safely (Yılmaz, 2017). The global aviation commerce is forecasted to continuously enlarge in forthcoming years by reason of the serious role of air transport in the present-day world. The International Air Transport Association (IATA) announced that approximately 3.8 billion passengers and 53.9 million metric tons of properties valued at nearly $5.5 trillion were carried in 2016. In accordance with the IATA annual report 2017, commercial aviation supplied 67.7 million jobs and devoted $3.0 trillion in commercial activities in 2016. It is predicted that commercial aviation industry will frequently grow and generated 90 million jobs and approximately $6 trillion in annual economic activities by 2034 (as compared to $3 trillion in 2016) (Yanga et al., 2019).

This dramatic expansion in aviation sector causes to consume large amount of jet fuels based on kerosene and to increase the environmental pollutions via exhaust gases emissions such as carbon monoxide (CO), carbon dioxide (CO_2), oxides of sulfur (SOx), oxides of nitrogen (NOx), hydrocarbon (HC), particulate matter (PM), toxic metals, soot and ashes. The increasing price of petroleum fuels and the growing environmental concerns of fossil fuel pollution have encouraged the aviation industry, especially propulsion manufacturer, to conduct research on the reduction of fuel consumption and exhaust emissions and on the increasing of engine efficiencies (Acikgoz et al., 2015; Baharozu et al., 2017; Coban et al., 2017; Letnik et al., 2018). The ways reducing the emissions in aviation sector can be the removal of older aircrafts and engines, the putting upon the new generation aero engines, the using of clean energy resources as biodiesel and hydrogen, the increasing the thermodynamic efficiency of aero engines and the improvements in operational management (Saravanamutto et al., 2009). The researchers explore the possible improvements of the thermodynamic efficiency and ecological effects of aero gas turbines for current engine technology (Ranasinghe et al., 2019).

Aero gas turbines are used to power both commercial and military aircrafts, unmanned aerial vehicles (UAVs) in the aviation industry known as air breathing engines, generate thrust to provide movement of aircraft. Performance analyses of different aero gas turbine engines and their subsystems are realized based on general aviation metrics and thermodynamic principles. Engine performance analyses with the aid of energy and exergy methods prove system efficiency, improvement potential, environmental impacts, and sustainability indicators (Şöhret, 2018a, Şöhret 2018b; Şöhret et al., 2015). While the energy analysis considers the fuel consumption and the desired product rate of the system, it is not concerned with the energy losses within the system.

Energy analysis includes the energy efficiency, the specific fuel consumption, the specific thrust, the thermal limit ratio, and the entalphy ratio of the investigated aero engines. However, the exergy analysis identifies the locations, magnitudes, and sources of thermodynamic inefficiencies within the investigated system. This data is very benefical for improving the overall efficiency and cost effectiveness of a system or for comparing performance of various systems (Koch et al., 2007). For eco-friendly aviation, researchers and engineers, who work on useful solutions for the aircraft gas turbine engines, aim to maximize the energy saving and to minimize the energy consumption for developing the environmentally benign propulsion systems and for reducing environmental impacts for sustainable aviation (Aydın et al., 2013). In this study, exergy analysis determines the exergy destruction rate within the system, the exergy losses rate from the system to the environment, the fuel exergy rate, the desired product exergy rate and some exergetic performance metrics such as the exergy efficiency, the exergetic improvement potential, the improvement exergy efficiency, fuel exergy depletion ratio, productivity lack ratio, and sustainable efficiency factor.

Micro turbojet engines have become very popular in various military and commercial applications in recent years. Some of these applications currently include cruise missiles, drones, Unmanned Aerial Vehicles (UVA's) and Micro Air Vehicles (MAV's). These vehicles are designed to carry out missions such as real-time reconnaissance, laser marking of targets, surveillance and even analyzing the air for potential chemical or biological warfare agents (Marsh, 2013). The main aim of this study is to analyze the general aviation, energetic, and exergetic performances of a micro turbojet engine (MTJE) at four different operation modes.

1. SYSTEM DESCRIPTION AND MATERIALS

1.1. General Description of a Micro Turbojet Engine (MTJE)

The investigated micro turbojet (MTJE) engine produces the maximum 125 N thrust at sea level condition. The photo of the MTJE engine running on the test bench and its simplified schematic are shown in Fig 1. The engine consists of the five major components: the air compressor (AC), combustion chamber (CC), gas turbine (GT), exhaust duct (ED) and the gas turbine mechanical shaft (GTMS).

1.2. Operation Modes of MTJE

For this study, the MTJE engine was operated in four different operation modes at the test bench. The MTJE engine was run at 60000 RPM for Mode-1, at 80000 RPM for Mode-2, at 100000 RPM for Mode-3 and at 120000 RPM for Mode-4 operation cases. The MTJE engine thrust was measured to be 45.04 N at Mode-1, 74.99 N at Mode-2, 100.00 N at Mode-3 and 124.99 N at Mode-4 while JP-8 jet fuel consumption of the MTJE engine was quantified to be 0.00225 kg/s at Mode-1, 0.00273 kg/s at Mode-2, 0.00325 kg/s at Mode-3 and 0.00388 kg/s at Mode-4, respectively. However, the air mass flow rate sucked by the MTJE engine was gauged to be 0.1324 kg/s at Mode-1, 0.1754 kg/s at Mode-2, 0.2075 kg/s at Mode-3 and 0.2412 kg/s at Mode-4. According to the mass conservation law, the exhaust gases mass rate is calculated to be 0.1347 kg/s at Mode-1, 0.1781 kg/s at Mode-2, 0.2108 kg/s at Mode-3 and 0.2451 kg/s at Mode-4. The basic measured data of MTJE engine is given in Table 1 in accordance with operation modes.

Table 1. Basic measured data of MTJE engine

Operation Modes	**Revolution Per Minute** (RPM)	**Fuel flow rate** $\dot{m}_F$ (kg/s)	**Air flow rate** $\dot{m}_A$ (kg/s)	**Exhaust gases rate** $\dot{m}_g$ (kg/s)	**Thrust** ET (N)	**Exhaust gases velocity** V (m/s)
Mode-1	60000	0.00225	0.1324	0.1347	45.04	334.5
Mode-2	80000	0.00273	0.1754	0.1781	74.99	421.0
Mode-3	100000	0.00325	0.2075	0.2108	100.00	474.5
Mode-4	120000	0.00388	0.2412	0.2451	124.99	510.0

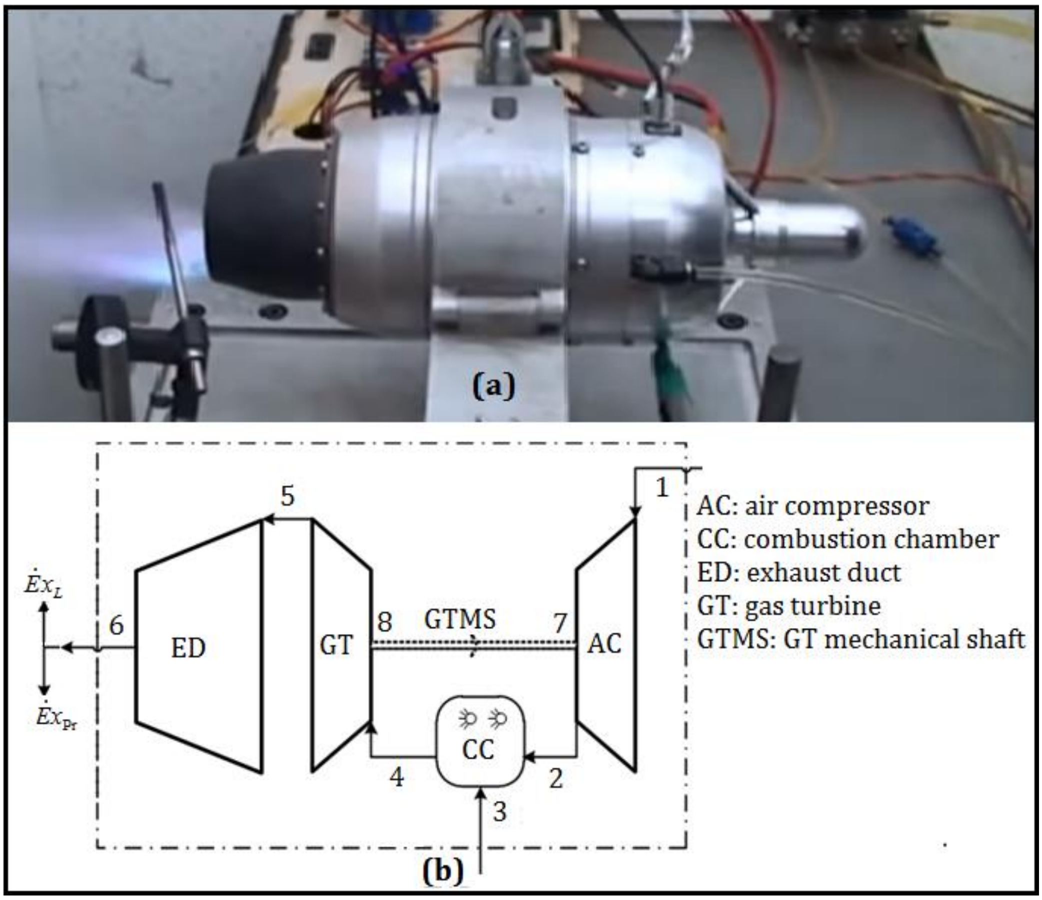

Fig.1. The MTJE engine (a) running on test bench, and (b) simplified drawing

1.3. Presumptions

The presumptions made for this study are given as follows:

- The engine runs under the steady-state and steady flow conditions.
- The engine is fueled by JP-8 jet fuel.
- The simplified chemical formula of jet fuel is assumed to be $C_{12}H_{23}$.
- The lower heating value (LHV) of JP-8 fuel is consider as 42800 kJ/kg.
- The combustion reaction is complete.
- The air and combustion gaseous are accepted to be an ideal-gas mixture.
- The compressor and the gas turbine considered are reckoned as adiabatic.
- The velocity of air mass flow entering the engine is taken zero.
- The cooling air mass flow is not considered for the analysis.

1.4. Specific Heat Capacity of Air and Exhaust Gases

Under the constant pressure, the specific heat capacity of air is only a function of temperature. It is estimated by (Balli and Hepbasli, 2013; Balli and Hepbasli 2014)**:**

$$c_{P,a}(T) = 1.04841 - \left(\frac{3.83719T}{10^4}\right) + \left(\frac{9.45378T^2}{10^7}\right) - \left(\frac{5.49031T^3}{10^{10}}\right) + \left(\frac{7.92981T^4}{10^{14}}\right) \quad (1)$$

The general combustion reaction equation of JP-8 jet fuel can be written as following form (Balli and Hepbasli, 2013):

$$C_{12}H_{23} + x_1\begin{pmatrix}0.7448N_2 + \\ 0.2059O_2 + \\ 0.0003CO_2 + \\ 0.019H_2O\end{pmatrix} \rightarrow x_2CO_2 + x_3H_2O + x_4O_2 + x_5N_2 \quad (2)$$

The specific heat capacity of the combustion gases is only a function of temperature under the constant pressure. It can be written in the following form from (Balli and Hepbasli, 2013):

$$c_{P,g}(T) = \lambda_1 + \frac{\lambda_2}{10^2}T + \frac{\lambda_{31}}{10^5}T^2 - \frac{\lambda_4}{10^9}T^3 \quad (3)$$

where the temperature is evaluated in K.

For each operation mode, the air-fuel ratio (AFR) and the constants $(x_1..x_5)$ for combustion reaction balance equation were calculated and given in Table 2.

Table 2. Air-fuel ratios and combustion reaction constant values

Operation Modes	**Air-to-Fuel Ratio** AFR (kg/s)	**Constants for combustion reaction equation**				
		x_1	x_2	x_3	x_4	x_5
Mode-1	58.844	343.892	12.103	18.034	53.057	266.447
Mode-2	64.249	375.224	12.113	18.629	59.509	290.724
Mode-3	63.846	372.871	12.112	18.585	59.024	288.900
Mode-4	62.165	363.053	12.109	18.398	57.003	281.294

However, the ideal gas constant (R_g) and the specific heat capacity constants $(\lambda_1..\lambda_4)$ of combustion gases were obtained and listed in Table 3 in accordance with operation modes.

Table 3. Combustion gas constant and specific heat capacity constant values

Operation Modes	**Combustion Gas Constant** R_g (kJ/kgK)	**Constants for specific heat capacity of combustion gases**			
		λ_1	λ_2	λ_3	λ_4
Mode-1	0.290135	0.98839	0.01145	0.01537	-0.06690
Mode-2	0.290141	0.98821	0.01107	0.01554	-0.06720
Mode-3	0.290140	0.98823	0.01109	0.01552	-0.06718
Mode-4	0.290139	0.98828	0.01120	0.01547	-0.06709

2. METHODOLOGY

2.1. General Aviation Performance Tools

The specific fuel consumption (*SFC*), specific thrust (*ST*), specific power (SP), overall pressure ratio (*OPR*) and thermal limit ratio (*TLR*) are used as the general aviation performance tools (Daly and Gunston, 1996; El- Sayed, 2008). The *SFC* determines that how much fuel flow is consumed to produce engine thrust or power. It is the ratio of the fuel flow rate to engine thrust (*ET*) or engine power $(\dot{E}_{\text{Pr}})$. Th *SFC* is foud by:

$$SFC = \frac{\dot{m}_3}{ET_{MTJE}} \tag{4}$$

$$SFC = \frac{\dot{m}_3}{\dot{E}_{\text{Pr},MTJE}} \tag{5}$$

The specific thrust (*ST*) determines the size of the engine required, since an engine with high specific thrust will require lower air flows to produce a given level of thrust than one with low specific thrust, and hence be smaller and lighter engine. The *ST* is increasing by the rising in the turbine inlet temperature when the engine overall pressure ratio is constant. Conversely, the *ST* is decreasing by the increasing in the overall pressure ratio of engine when the engine turbine inlet temperature is constant. The *ST* is calculated by the ratio of the engine thrust to air flow rate of the engine as flows:

$$ST = \frac{ET_{MTJE}}{\dot{m}_1} \tag{6}$$

The *SP* is found by the ratio of the engine power to air flow rate of the engine as follows

$$SP = \frac{\dot{E}_{\text{Pr},MTJE}}{\dot{m}_1} \tag{7}$$

The overall pressure ratio (*OPR*) is the compressor pressure ratio and defined as the ratio of the compressor outlet pressure to the compressor inlet pressure. It is estimated by:

$$OPR = \frac{P_2}{P_1} \tag{8}$$

The turbine pressure ratio (*TPR*) is the gas turbine pressure ratio and described as the ratio of the gas turbine inlet pressure to the outlet pressure. It is counted by:

$$TPR = \frac{P_4}{P_5} \tag{9}$$

The thermal limit ratio (*TLR*) determines the maximum temperature resistance of materials used on the combustion chamber and turbine section of the engine. It is accounted by the ratio of the combustion chamber outlet (turbine inlet) temperature to the reference environment temperature as follows:

$$TLR = \frac{T_4}{T_0} \tag{10}$$

2.2. Energy Analysis and Energetic Aspects

Energy analysis includes the energy balance equations, mass balance equations, governing equations for engine components and energetic performance metrics. According to Fuel-Product (*F-Pr*) rule, the energy balance equation for any control volume at steady state is written as (Balli et al., 2018; Balli, 2019):

$$\dot{E}_F = \dot{E}_{\mathrm{Pr}} + \dot{E}_L \tag{11}$$

where $\dot{E}_F$, $\dot{E}_{\mathrm{Pr}}$ and $\dot{E}_L$ denote the input energy rate as fuel energy, the desired product energy rate and the energy loss rate that does not convert to the desired product. The fuel energy rate and product energy rate of the MTJE can be estimated from (Balli et al., 2018; Balli, 2019):

$$\dot{E}_{F,MTJF} = \dot{E}_{3,MTJE} = \dot{m}_3 LHV_F \tag{12}$$

$$\dot{E}_{\mathrm{Pr},MTJE} = \dot{m}_6 \frac{V_6^2}{2000} \tag{13}$$

The governing equations for MTJE's subsystems are given as follows (El-Sayed, 2008; Balli and Hepbasli, 2013):

Air Compressor (AC):

$$\dot{m}_1 = \dot{m}_2 \tag{14}$$

$$T_2 = T_1 \left\{ 1 + \frac{1}{\eta_{AC,isen}} \left(\frac{P_2}{P_1} \right)^{\frac{\kappa_{air} - 1}{\kappa_{air}}} - 1 \right\} \tag{15}$$

$$\kappa_{air} = \frac{1}{1 - \frac{R_{air}}{c_{P,air}}} \tag{16}$$

$$\dot{E}_1 = \dot{m}_1 \left(c_{P_1} T_1 - c_{P_0} T_0 \right) \tag{17}$$

$$\dot{E}_2 = \dot{m}_2\left(c_{P_2}T_2 - c_{P_0}T_0\right) \tag{18}$$

$$\dot{E}_8 = \dot{W}_{AC} = \dot{E}_2 - \dot{E}_1 \tag{19}$$

Combustion Chamber (CC):

$$\dot{m}_4 = \dot{m}_2 + \dot{m}_3 \tag{20}$$

$$\dot{E}_3 = \dot{m}_3 LHV_F \tag{21}$$

$$\dot{E}_4 = \dot{m}_4\left(c_{P_4}T_4 - c_{P_0}T_0\right) \tag{22}$$

$$\eta_{CC} = \frac{\dot{E}_4 - \dot{E}_2}{\dot{E}_3} \tag{23}$$

Gas Turbine (GT):

$$\dot{m}_4 = \dot{m}_5 \tag{24}$$

$$T_5 = T_4\left\{1 - \eta_{GT,isen}\left[1 - \left(\frac{P_4}{P_5}\right)^{\frac{1-\kappa_{gas}}{\kappa_{gas}}}\right]\right\} \tag{25}$$

$$\kappa_{gas} = \frac{1}{1 - \frac{R_{gas}}{c_{P,gas}}} \tag{26}$$

$$\dot{E}_5 = \dot{m}_5\left(c_{P_5}T_5 - c_{P_0}T_0\right) \tag{27}$$

$$\dot{E}_7 = \dot{W}_{GT} = \dot{E}_4 - \dot{E}_5 \tag{28}$$

Gas Turbine Mechanical Shaft (GTMS):

$$\eta_{GTMS} = \frac{\dot{E}_8}{\dot{E}_7} = \frac{\dot{W}_8}{\dot{W}_7} \tag{29}$$

Exhaust Duct (ED):

$$\dot{m}_5 = \dot{m}_6 \tag{30}$$

$$\dot{E}_6 = \dot{m}_6\left(c_{P_6}T_6 - c_{P_0}T_0\right) \tag{31}$$

$$\eta_{ED} = \frac{\dot{E}_6}{\dot{E}_5} \tag{32}$$

Energy efficiency and enthalpy ratio are used to analyze the energetic performance of MTJE. The energy efficiency of the MTJE is the ratio of product energy rate to fuel energy rate. It is obtained by:

$$\eta_{MTJE} = \frac{\dot{E}_{\mathrm{Pr},MTJE}}{\dot{E}_3} \tag{33}$$

The enthalpy ratio (*ER*) is estimated by the ratio of the combustion chamber outlet (turbine inlet) empathy to the enthalpy of reference environment as follows:

$$ER = \frac{h_{out,CC}}{h_0} = \frac{c_{P_3} T_3}{c_{P_0} T_0} \tag{34}$$

2.3. Exergetic analysis and exergetic aspects

Exergy analysis is a thermodynamic method that uses the conservation laws of mass and energy together with the second law of thermodynamics for analyzing, designing, and developing the thermal conversion systems. The exergy is a helpful tool to recognize locations, types and magnitudes of wastes and losses, and to obtain the meaningful efficiencies. In accordance with Fuel-Product (*F-Pr*) rule, exergy balance for any control volume at steady state is written as (Balli et al., 2018; Balli, 2019):

$$\dot{E}x_F = \dot{E}x_{\mathrm{Pr}} + \dot{E}x_{WE} = \dot{E}x_{\mathrm{Pr}} + \dot{E}x_D + \dot{E}x_L \tag{35}$$

where $\dot{E}x_F$, $\dot{E}x_{\mathrm{Pr}}$, $\dot{E}x_{WE}$, $\dot{E}x_D$ and $\dot{E}x_L$ represent the fuel exergy rate, the product exergy rate, waste exergy rate, exergy destruction rate and exergy losses rate, respectively. The product exergy rate and fuel exergy rate of the MTJE can be calculated via (Balli, 2017a, b, c; Balli, 2019; Balli and Hepbasli, 2014; Balli et al., 2018):

$$\dot{E}x_{\mathrm{Pr},MTJE} = \dot{m}_6 \frac{V_6^2}{2000} \tag{36}$$

$$\dot{E}x_{F,MTJE} = \dot{E}x_3 = \dot{m}_3 \gamma_F LHV_F \tag{37}$$

Here the γ_F is the liquid fuel exergy grade function. It is obtained by (Rakapoulos and Giakoumis, 2006; Balli and Hepbasli, 2014):

$$\gamma_F \cong 1.04224 + 0.011925 \frac{b}{a} - \frac{0.042}{a} \tag{38}$$

For JP-8 jet fuel, it is calculated to be 1.0616.

The exergy rate of air and combustion gases streams is estimated by (Yuksel et al., 2020; Balli et al., 2018; Balli, 2017a, b, c; Balli, 2019; Balli and Hepbasli, 2014):

$$\dot{E}x = \dot{m}\left\{c_{P(T)}\left[T - T_o - T_o \ln\left(\frac{T}{T_o}\right)\right] + RT_o \ln\left(\frac{P}{P_o}\right)\right\} \quad (39)$$

The exergy balance equations for MTJE engine and its subsections are given in Table 4.

Table 4. Exergy balance relations for whole engine and its subsections

Comp.	Fuel	Product	Balance relations	Eqn.No.
AC	$\dot{W}_8$	$\left(\dot{E}x_2 - \dot{E}x_1\right)$	$\dot{E}x_{D,AC} = \dot{W}_8 - \left(\dot{E}x_2 - \dot{E}x_1\right)$	(40)
CC	$\dot{E}x_3$	$\left(\dot{E}x_4 - \dot{E}x_2\right)$	$\dot{E}x_{D,CC} = \dot{E}x_3 - \left(\dot{E}x_4 - \dot{E}x_2\right)$	(41)
GT	$\left(\dot{E}x_4 - \dot{E}x_5\right)$	$\dot{W}_7$	$\dot{E}x_{D,GT} = \left(\dot{E}x_4 - \dot{E}x_5\right) - \dot{W}_7$	(42)
ED	$\dot{E}x_5$	$\dot{E}x_6$	$\dot{E}x_{D,ED} = \dot{E}x_5 - \dot{E}x_6$	(43)
GTMS	$\dot{W}_7$	$\dot{W}_8$	$\dot{E}x_{D,GTMS} = \dot{W}_7 - \dot{W}_8$	(44)
MTJE	$\dot{E}x_3$	$\dot{E}x_{\mathrm{Pr},MTJE}$	$\dot{E}x_{WE,MTJE} = \dot{E}x_3 - \dot{E}x_{\mathrm{Pr},MTJE}$	(45)
			$\dot{E}x_{WE,MTJE} = \dot{E}x_{L,MTJE} + \dot{E}x_{D,MTJE}$	(46)
			$\dot{E}x_{D,MTJE} = \dot{E}x_{D,AC} + \dot{E}x_{D,CC} + \dot{E}x_{D,GT} + \dot{E}x_{D,ED} + \dot{E}x_{D,GTMS}$	(47)
			$\dot{E}x_{L,MTJE} = \dot{E}x_6 - \dot{E}x_{\mathrm{Pr},MTJE}$	(48)

Some useful exergy assessment metrics are identified in the literature (Balli and Hepbasli 2014; Balli, 2017d; Balli, 2019, Şöhret, 2018a, b). In addition to the exergy efficiency, the exergetic improvement potential, the improved exergy efficiency, the waste exergy ratio, fuel exergy waste ratio, the productivity lack ratio, and sustainable efficiency factor are beneficial tools for evaluation of the exergetic performances of the MTJE and its subsystem. These performance tools are listed in Table 5.

3. RESULTS and DISCUSSIONS

For this study, the values of the pressure, temperature, air flow and mass flow at the station numbers of MTJE illustrated in Figure 1 were measured at test bench. Then, the heat capacity values of air and combustion gases, enthalpy values of air and combustion gases, energy and exergy rates of air, combustion gases, shaft work and engine production were calculated from the thermodynamic equations given in Section 2. The stream type, pressure, temperature, mass flow rate, specific heat capacity, enthalpy, energy rate, and exergy rate of the MTJE's streams at four different operation modes are listed in Tables 6 in accordance with their station numbers as specified in Fig.1.

Table 5. Exergetic performance metrics for MTJE engine and its subsections

Performance Metrics	**Unit**	**Relation**	**Eqn. No.**
Exergy efficiency	(%)	$\psi_{MTJE} = \frac{\dot{E}x_{\mathrm{Pr},MTJE}}{\dot{E}x_{F,MTJE}}$ $\psi_k = \frac{\dot{E}x_{out,k}}{\dot{E}x_{in,k}}$	(49a) (49b)
Exergetic improvement potential	(kW)	$\dot{E}xIP = (1-\psi)\dot{E}x_D$	(50)
Improved exergy efficiency	(%)	$\Psi_{MTJE} = \frac{\dot{E}x_{\mathrm{Pr},MTJE}}{\dot{E}x_{F,MTJE} - \dot{E}xIP_{MTJE}}$ $\Psi_k = \frac{\dot{E}x_{out,k}}{\dot{E}x_{in,k} - \dot{E}xIP_k}$	(51a) (51b)
Fuel exergy waste ratio	(%)	$FExWR_{MTJ} = \frac{\dot{E}x_{WE,MTJE}}{\dot{E}x_{F,MTJE}}$ $FExWR_k = \frac{\dot{E}x_{D,k}}{\dot{E}x_{F,MTJE}}$	(52a) (52b)
Productivity lack ratio	(%)	$PLR_{MTJ} = \frac{\dot{E}x_{WE,MTJE}}{\dot{E}x_{\mathrm{Pr},MTJE}}$ $PLR_k = \frac{\dot{E}x_{D,k}}{\dot{E}x_{\mathrm{Pr},MTJE}}$	(53a) (53b)
Sustainable efficiency factor	(-)	$SEF_{MTJE} = \frac{1}{1-\psi_{MTJE}}$ $SEF_k = \frac{1}{1-\psi_k}$	(54a) (54b)

Table 6. Measured and calculated thermodynamic data at the station numbers of MTJE

Modes	**Stations**	**Streams**	P (kPa)	T (K)	$\dot{m}$ $\left(\frac{kg}{s}\right)$	c_P $(\frac{kJ}{kgK})$	h $(\frac{kJ}{kg})$	$\dot{E}$ (kW)	$\dot{E}x$ (kW)
	0	Air	101.325	288.15	0.0000	1.00375	289.23	0.000	0.000
Mode-1	1	Air	101.325	288.15	0.1324	1.00375	289.23	38.294	0.000
	2	Air	301.949	418.50	0.1324	1.01559	425.02	56.273	15.023
	3	Fuel	227.500	298.15	0.0023	-----	42800.00	96.300	102.232
	4	Gases	286.851	914.15	0.1347	1.17034	1069.87	144.058	57.939
	5	Gases	130.387	814.15	0.1347	1.14734	934.11	125.778	37.863
	6	Gases	127.779	811.15	0.1347	1.14665	930.10	125.238	37.315
	7	Work						18.280	18.280
	8	Work						17.979	17.979
	$\dot{E}x_{\mathrm{Pr}}$	Product						7.533	7.533
Mode-2	1	Air	101.325	288.15	0.1754	1.00375	289.23	50.731	0.000
	2	Air	317.147	421.50	0.1754	1.01602	428.25	75.115	20.785
	3	Fuel	227.500	298.15	0.0027	-----	42800.00	116.844	124.042
	4	Gases	301.290	917.95	0.1781	1.16880	1072.90	191.116	77.841
	5	Gases	133.907	815.25	0.1781	1.14534	933.74	166.327	50.550
	6	Gases	131.228	812.25	0.1781	1.14677	931.47	165.922	49.912
	7	Work						24.789	24.789
	8	Work						24.385	24.385
	$\dot{E}x_{\mathrm{Pr}}$	Product						15.786	15.786
Mode-3	1	Air	101.325	288.15	0.2075	1.00375	289.23	60.015	0.000
	2	Air	332.346	425.50	0.2075	1.01660	432.56	89.757	25.664
	3	Fuel	227.500	298.15	0.0033	-----	42800.00	139.100	147.669
	4	Gases	315.729	924.15	0.2108	1.17024	1081.48	227.922	94.061
	5	Gases	134.353	818.42	0.2108	1.14612	938.01	197.685	60.399
	6	Gases	131.666	815.92	0.2108	1.14764	936.38	197.342	59.725
	7	Work						30.237	30.237
	8	Work						29.742	29.742
	$\dot{E}x_{\mathrm{Pr}}$	Product						23.725	23.725
Mode-4	1	Air	101.325	288.15	0.2412	1.00375	289.23	69.762	0.000
	2	Air	349.571	429.50	0.2412	1.01720	436.89	105.377	31.164
	3	Fuel	227.500	298.15	0.0039	-----	42800.00	166.064	176.294
	4	Gases	332.093	939.65	0.2451	1.17445	1103.57	270.463	113.810
	5	Gases	135.548	831.35	0.2451	1.14976	955.85	234.261	72.994
	6	Gases	132.837	828.85	0.2451	1.15068	953.74	233.743	72.174
	7	Work						36.203	36.203
	8	Work						35.615	35.615
	$\dot{E}x_{\mathrm{Pr}}$	Product						31.873	31.873

3.1. The Results of General Aviation Assessment

When the engine power lever advances step by step from Mode-1 to Mode-4, the revaluation speed, air mass flow, fuel mass flow, engine thrust and exhaust gases velocity increase as seen from Table 1. Using the data given in Table 1, the specific fuel consumption (SFC) and specific thrust (ST) were obtained to be 0.0500 g/N.s and 0.3402 N/g/s for Mode-1, 0.0364 g/N.s and 0.4276 N/g/s for Mode-2, 0.0325 g/N.s and 0.4819 N/g/s for Mode-3, and 0.0310 g/N.s and 0.5182 N/g/s for Mode-4 operation modes. Hovewer, the specific fuel consumption (SFC) and specific power (SP) were estimated to be 0.2987 g/kW.s and 0.0569 kW/g/s for Mode-1, 0.1729 g/kW.s and 0.0900 kW/g/s for Mode-2, 0.1370 g/kW.s and 0.1143 kW/g/s for Mode-3, and 0.1277 g/kW.s and 0.1321 kW/g/s for Mode-4 operation modes by using the engine power rates served in Table 1. These results indicate that the SFC reduces while the ST and the SP rise via an increasing in thrust or power. Additionally, the overall pressure ratio (OPR), the turbine pressure ratio (*TPR*) and thermal limit ratio (TLR) arise from 2.98, 2.20 and 3.173 at Mode-1 to 3.45, 2.45 and 3.261 at Mode-4, respectively. All results of general aviation performance tools are indexed in Table 7.

Table 7. General aviation performance metrics of MTJE for different operation modes.

Metrics	Units	Mode-1	Mode-2	Mode-3	Mode-4
SFC	(g/N. s)	0.0500	0.0364	0.0325	0.0310
SFC	(g/kW. s)	0.2987	0.1729	0.1370	0.1217
ST	(N/g/s)	0.3402	0.4276	0.4819	0.5182
SP	(kW/g/s)	0.0569	0.0900	0.1143	0.1321
OPR	(-)	2.98	3.13	3.28	3.45
TPR	(-)	2.20	2.25	2.35	2.45
TLR	(-)	3.173	3.186	3.207	3.261

3.2. The Results of Energy Analysis

The results of energy analysis are tabulated in Table 8. According to Table 8, the energy efficiency of the MTJE engine rises from 7.82% at Mode-1 to 19.19% at Mode-4 by the increasing in the engine product rate. Similarly, the isentropic efficiency of air compressor (AC) increments from 81.01% at Mode-1 to 86.61% at Mode-4 while the isentropic efficiency of gas turbine (GT) drops from 61.61% at Mode-1 to 58.04% at Mode-4.

Table 8. Energetic performance metrics of MTJE and its subcomponents

Metrics	Units	Mode-1	Mode-2	Mode-3	Mode-4
$\dot{E}_{F,MTJE}$	(kW)	96.30	116.84	139.10	166.06
$\dot{E}_{\mathrm{Pr},MTJE}$	(kW)	7.53	15.79	23.73	31.87
$\dot{E}_8 = \dot{W}_{AC}$	(kW)	17.98	24.38	29.74	35.61
$\dot{E}_7 = \dot{W}_{GT}$	(kW)	18.28	24.79	30.24	36.20
η_{MTJE}	(%)	7.82	13.51	17.06	19.19

$\eta_{ise,AC}$	(%)	81.01	83.36	84.85	86.61
$\eta_{ise,GT}$	(%)	61.61	61.36	59.93	58.04
η_{CC}	(%)	90.16	98.28	98.32	98.39
η_{ED}	(%)	99.38	99.65	99.67	99.68
η_{GTMS}	(%)	98.35	98.37	98.36	98.38
ER	(-)	3.70	3.71	3.74	3.81

These results show that an increasing in the compressor pressure ratio escalates the compressor isentropic efficiency while an increment in the turbine pressure ratio lowers the compressor isentropic efficiency. The mechanical efficiency of the gas turbine mechanical shaft (GTMS) is obtained to be approximately 98.37% for all operation modes. On the other hand, the energy efficiency of combustion chamber (CC) steps up from 90.16% at Mode-1 to 98.39% at Mode-4 when the energy efficiency of exhaust duct (ED) climbs from 99.38% at Mode-1 to 99.68% at Mode-4 depending on the operation modes. Finally, enthalpy ratio (ER) of MTJE increases from 3.70 at Mode-1 to 3.81 at Mode-4. The reason of this progress is that the enthalpy (*h*) value is 1069.87 kJ/kg at Mode-1 while it is 1103.57 kJ/kg at Mode-4.

3.3. The Results of Exergy Analysis

According to F-Pr rule, the values of the fuel exergy rate, product exergy rate, exergy destruction rate, exergy losses rate and waste exergy rate at operation modes were obtained for the MTJE and its subsystems and given in Table 9. Additionally, using the equations in Table 5, the exergetic performance metrics of MTJE and its subsystem are calculated and listed in Table 10 in accordance with operation modes. The main findings of the exergetic analysis are summarized as follows:

- The exergy efficiency of MTJE is calculated to be 7.369% at Mode-1, 12.726% at Mode-2, 16.067% at Mode-3 and 18.079% at Mode-4 operation modes. When the exergy efficiency values of subcomponents are reviewed, the exergy efficiency of AC increases from 83.560% at Mode-1 to 87.503% at Mode4 while the exergy efficiency of GT decreases from 91.79% at Mode-1 to 89.845% at Mode-4. These results are are also compatible with the isentropic efficiencies of AC and GT in exergy analysis results. The exergy efficiency of CC rises from 41.978% at Mode-1 to 46.880% Mode-4 operation modes. On the other hand, the exergy efficiency values of GTMS and ED are approximately the same in all operation modes. The exergy efficiency values of the engine and its components are illustrated in Fig.2.

- Between the components, the CC has the maximum exergetic improvement potential rates for all operation modes since the CC has the minimum exergy efficiency values and maximum exergy destruction rates that the combustion processes has high thermodynamic irreversibility caused by chemical reaction, heat transfer, friction, and mixing. The changes in the exergetic improvement potentials of MTJE and its subsystems are demonstrated in Fig.3.
- If the requirement improvement and development are realized in the MTJE, the exergy efficiency values of the MTJE and its subsystems will rise for all operation modes because the waste exergy rate (losses and destruction) will be reduced. This case can be clearly seen from the modified exergy efficiency values in Table 10. Figure 4-9 indicates the changes in the actual exergy efficiency and modified exergy efficiency of the MTJE and its subsegments.

Table 9. Exergy rates for MTJE and its subsystems

Modes	Components	$\dot{E}x_F$ (kW)	$\dot{E}x_{\mathrm{Pr}}$ (kW)	$\dot{E}x_D$ (kW)	$\dot{E}x_L$ (kW)	$\dot{E}x_{WE}$ (kW)
Mode-1	AC	17.979	15.023	2.956	0.000	2.956
	CC	102.232	42.915	59.317	0.000	59.317
	GT	20.076	18.280	1.796	0.000	1.796
	GTMS	18.280	17.979	0.301	0.000	0.301
	ED	37.863	37.315	0.548	0.000	0.548
	MTJE	102.232	7.533	64.917	29.782	94.699
Mode-2	AC	24.385	20.785	3.600	0.000	3.600
	CC	124.042	57.057	66.985	0.000	66.985
	GT	27.291	24.789	2.502	0.000	2.502
	GTMS	24.789	24.385	0.405	0.000	0.405
	ED	50.550	49.912	0.639	0.000	0.639
	MTJE	124.042	15.786	74.130	34.126	108.256
Mode-3	AC	29.742	25.664	4.078	0.000	4.078
	CC	147.669	68.397	79.271	0.000	79.271
	GT	33.663	30.237	3.426	0.000	3.426
	GTMS	30.237	29.742	0.495	0.000	0.495
	ED	60.399	59.725	0.674	0.000	0.674
	MTJE	147.669	23.725	87.944	35.999	123.943
Mode-4	AC	35.615	31.164	4.451	0.000	4.451
	CC	176.294	82.646	93.647	0.000	93.647
	GT	40.816	36.203	4.613	0.000	4.613
	GTMS	36.203	35.615	0.588	0.000	0.588
	ED	72.994	72.174	0.821	0.000	0.821
	MTJE	176.294	31.873	104.120	40.301	144.421

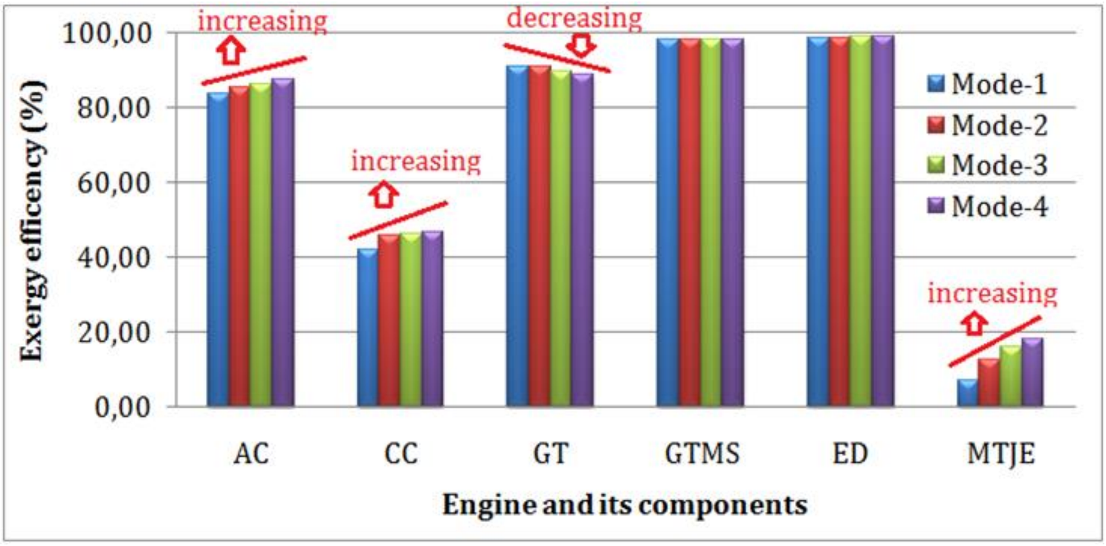

Figure 2. The exergy efficiency values of the MTJE and its components

Table 10. Exergetic performance metrics for MTJE and its subcomponents

Modes	**Components**	ψ (%)	$\dot{E}xIP$ (kW)	Ψ (%)	*FExWR* (%)	*PLR* (%)	*SEF* (%)
Mode-1	AC	83.560	1.749	85.881	2.891	39.237	6.083
	CC	41.978	123.899	63.282	58.022	787.423	1.723
	GT	91.056	0.578	91.790	1.756	23.836	11.181
	GTMS	98.352	0.018	98.379	0.295	3.999	60.678
	ED	98.554	0.029	98.574	0.536	7.269	69.144
	MTJE	7.369	126.273	11.217	92.631	1257.121	1.080
Mode-2	AC	85.237	1.913	87.136	2.902	22.804	6.774
	CC	45.998	130.223	64.934	54.002	424.331	1.852
	GT	90.833	0.826	91.602	2.017	15.849	10.908
	GTMS	98.367	0.024	98.393	0.326	2.564	61.238
	ED	98.737	0.029	98.752	0.515	4.045	79.155
	MTJE	12.726	133.015	18.125	87.274	685.771	1.146
Mode-3	AC	86.290	2.013	87.943	2.761	17.187	7.294
	CC	46.318	153.196	65.069	53.682	334.123	1.863
	GT	89.823	1.255	90.763	2.320	14.439	9.827
	GTMS	98.363	0.029	98.389	0.335	2.087	61.075
	ED	98.884	0.027	98.896	0.457	2.842	89.589
	MTJE	16.067	156.520	22.771	83.933	522.412	1.191
Mode-4	AC	87.503	2.002	88.891	2.525	13.964	8.002
	CC	46.880	179.083	65.308	53.120	293.816	1.883
	GT	88.698	1.877	89.845	2.617	14.474	8.848
	GTMS	98.376	0.034	98.402	0.334	1.845	61.567
	ED	98.876	0.033	98.888	0.466	2.575	88.932
	MTJE	18.079	183.030	25.406	81.921	453.118	1.221

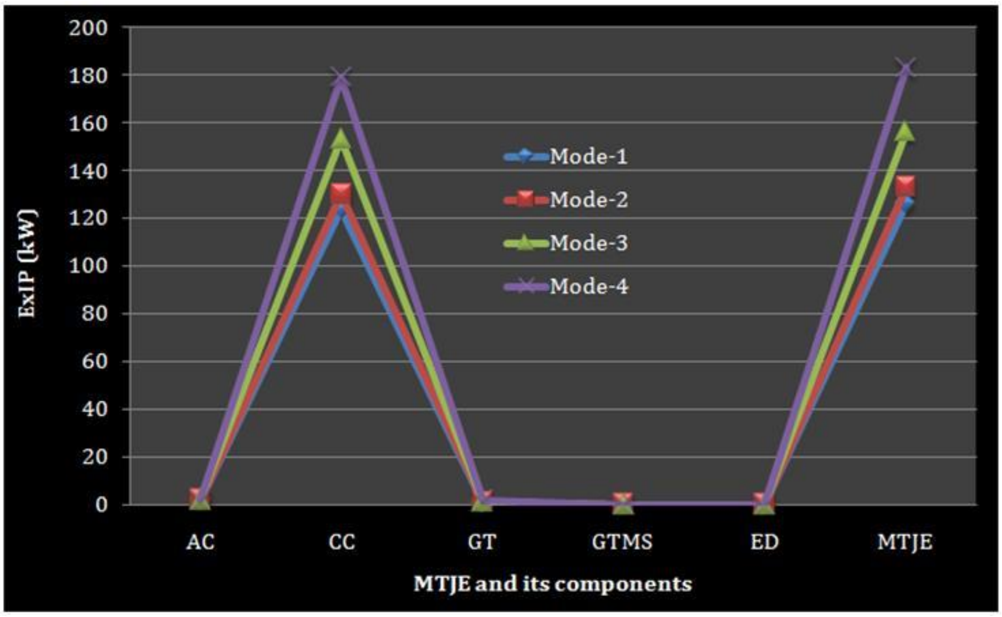

Figure 3. The exergetic improvement potential of engine and its components

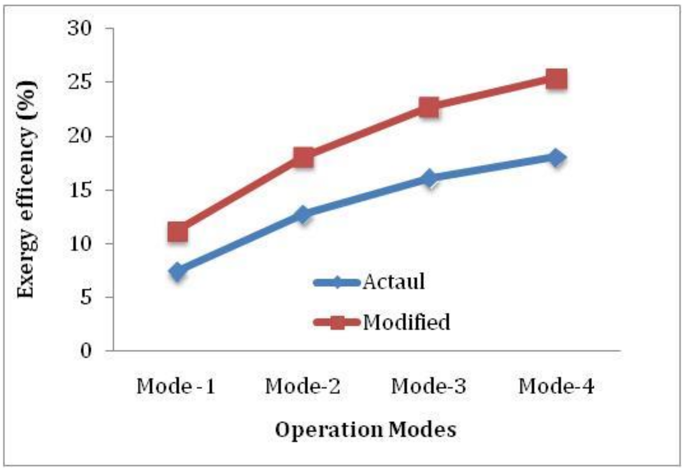

Figure 4. Actual and modified exergy efficiency of MTJE

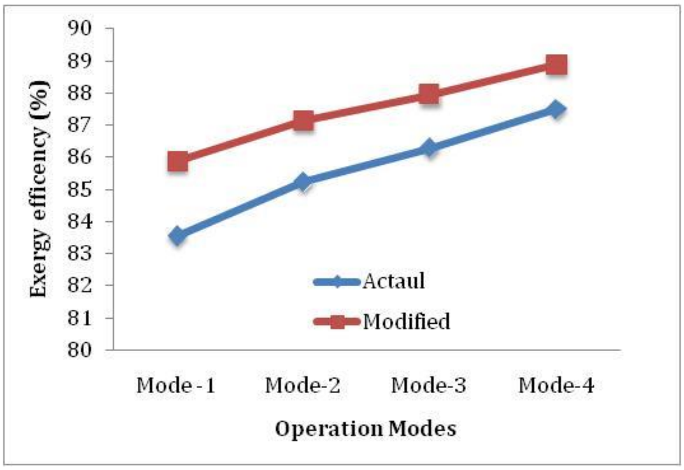

Figure 5. Actual and modified exergy efficiency of AC

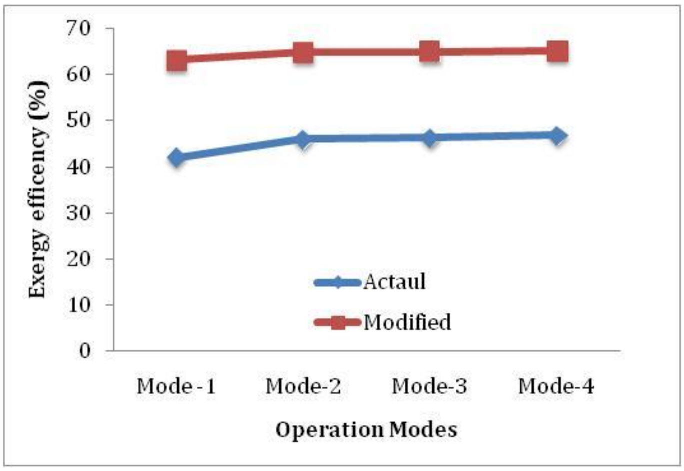

Figure 6. Actual and modified exergy efficiency of CC

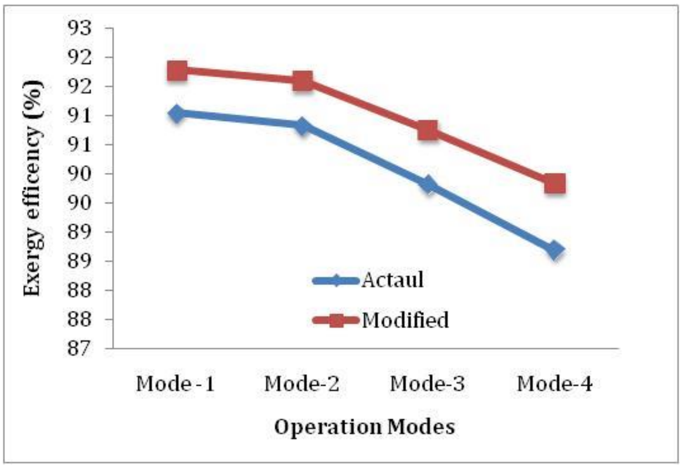

Figure 7. Actual and modified exergy efficiency of GT

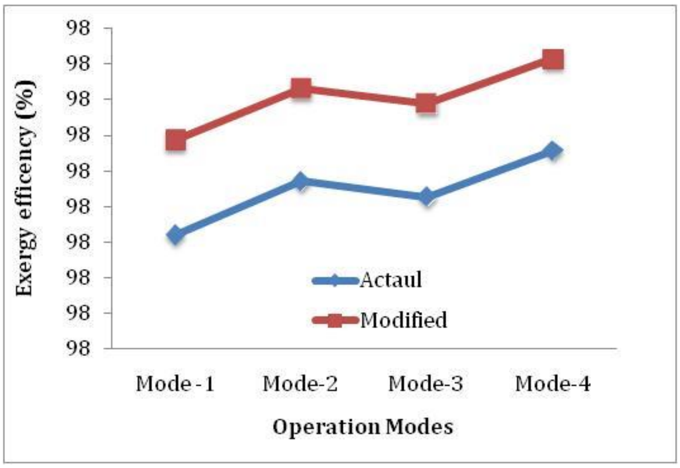

Figure 8. Actual and modified exergy efficiency of GTMS

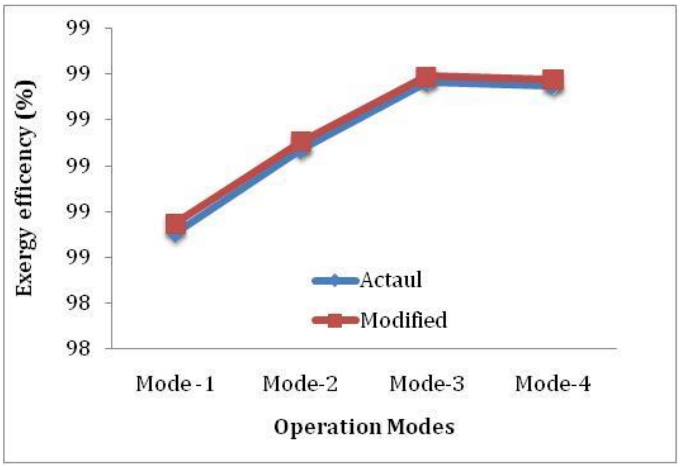

Figure 9. Actual and modified exergy efficiency of ED

- Fuel exergy waste ratio (FExWR) shows that how much fuel exergy rate wastes via exergy destruction and losses. Between the components, the CC has the maximum FExWR values for all operation modes since the CC has maximum exergy destruction rates. The FExWR values of the MTJE and its components are shown in Figure 10.

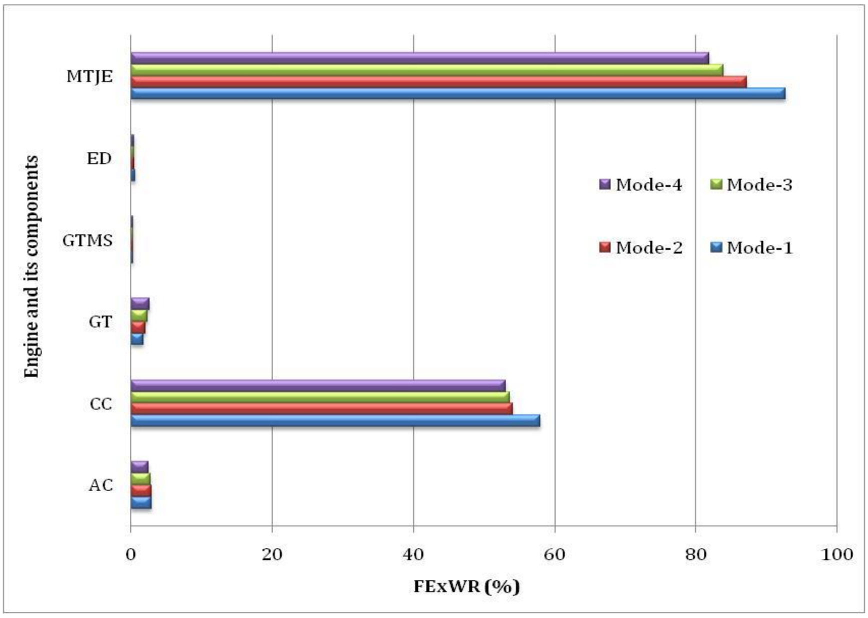

Figure 10. Fuel exergy waste ratio values of MTJE and its components.

- Productivity lack ratio (PLR) expresses that how much product exergy rate loses by waste exergy rate. Between the components, the CC has the maximum PLR values for all operation modes since the CC has maximum exergy destruction rates. The PLR values of the MTJE and its components are showed in Figure 11. Figure 11 indicates that PLR values reduce depending on operation modes. The PLR is the minimum at Mode-4 operation because the engine and the CC have the maximum efficiency values at this operation mode.

- The components or system with high exergy losses and destruction are more harmful to environment. Sustainable efficiency factor (SEF) states which components are sustainable and less environmental impacts. The SEF values of the MTJE and its subcomponents are illustrated in Figure 12. According to Figure 12, the ED has the maximum SEF values by high exergy efficiency values for all operation modes while the CC has the minimum SEF values via low exergy efficiency values for all operation modes.

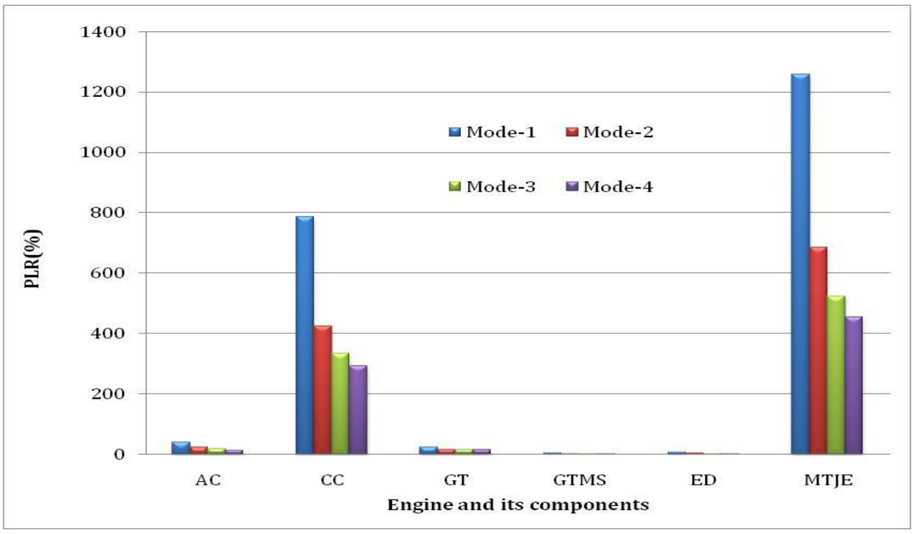

Figure 11. Productivity lack ratios of the MTJE and its components

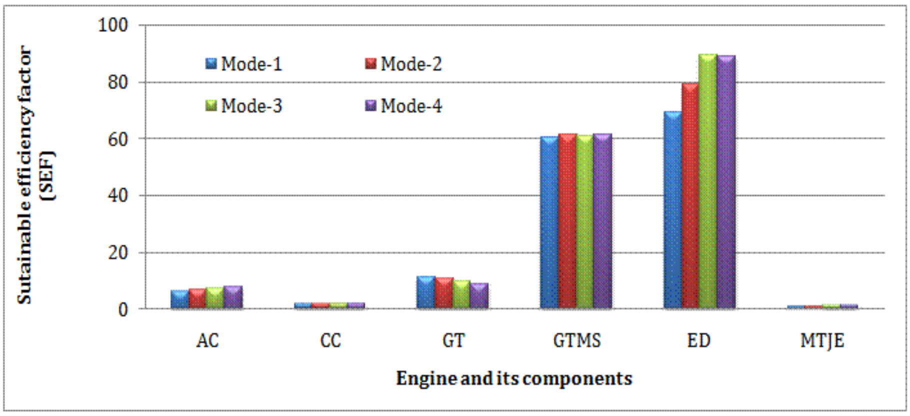

Figure 12. Sustainable efficiency factors of the MTJE and its components

4. CONCLUSION

This study presents the general aviation, energetic and exergetic performance metrics to analyze the evaluation of a micro turbojet engine used on drome and UAV. These metrics help the system designers, owners, and researchers to measure the system performance level and to develop the system and its subsystems. The significant results of this study are abridged as flows:

- The specific fuel consumption (SFC) of the MTJE is 0.0500 g/N.s at Mode-1, 0.0364 g/N.s at Mode-2, 0.0325 g/N.s at Mode-3, and 0.0310 g/N.s at Mode-4 operation modes. While the specific thrust (ST) is 0.3402 N/g/s at Mode-1, 0.4276 N/g/s at Mode-2, 0.4819 N/g/s at Mode-3, and 0.5182 N/g/s at Mode-4 operation modes, respectively.
- Thermal limit ratio (TLR) of the MTJE is obtained to be 3.1725 at Mode-1, 3.1857 at Mode-2, 3.2072 at Mode-3, and 3.2610 at Mode-4, respectively
- The energy efficiency of the MTJE is determined to be 7.730% at Mode-1, 13.510% at Mode-2, 17.070% at Mode-3, and 19.190% at Mode-4 when the exergy efficiency of the MTJE is found to be 7.367% at Mode-1, 12.726% at Mode-2, 16.067 at Mode-3, and 18.079% at Mode-4, respectively. Exergy efficiency values are lower than energy efficiency values because the fuel exergy is higher than the fuel energy.
- By an increasing in air flow, fuel flow and engine thrust, the isentropic efficiency of air compressor (AC) increases from 81.010% to 86.610% when the isentropic efficiency of gas turbine (GT) decreases from 61.610% to 58.040%. Similarly, the exergy efficiency of AC rises from 83.560% to 87.503% while the exergy efficiency of GT declines from 91.056% to 88.698%.
- Between the components, the CC has the lowest exergy efficiency values (from 41.978% to 46.880%), the lowest sustainable efficiency factors (from 1.723 to 1.883), the highest exergetic improvement potential rates (from 123.899 kW to 179.083 kW), the highest fuel exergy waste ratios (from 58.022% to 53.120%) and the highest productivity lack ratios (from 787.423% to 293.816%) depending on the operation modes since the CC has the maximum exergy destruction rates.
- If any improvement or development is made on the components, the exergetic performance indicators of both the MTJE and its subsystems will be thrived. This case can be clearly seen from the modified exergy efficiency values.
- When the exergetic performance parameters are taken into the consideration, the worst component and bad factor of the system is the combustion chamber by far. Therefore, all exergetic performance indicators show that the system designer, owner, and researchers focus on the components of the AC and CC to improve the exergetic efficiency values of these components.

The recommended performance metrics and methodology in this investigation can be beneficial to analyze the similar aviation systems and other energy conversion systems.

NOMENCLATURE

AC	air compressor
AFR	air-fuel ratio
CC	combustion chamber
c_P	specific heat capacity (kJ/kg. K)
$\dot{E}$	energy rate (kW)
ED	exhaust duct nozzle
ER	enthalpy ratio (-)
EP	engine power (kw)
ET	engine thrust (kN)
$\dot{E}x$	exergy rate (kW)
$\dot{E}xIP$	exergy improvement potential rate (kW)
FExWR	fuel exergy waste ratio (%)
GT	gas turbine
GTMS	GT mechanical shaft
h	enthalpy (kJ/kg)
LHV	lower heating value of fuel (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
MTJE	micro turbojet engine
P	pressure (kPa)
PLR	Productivity lack ratio (%)
R	universal gas constant (kJ/kg K)
SEF	sustainable efficiency factor (-)
SFC	specific fuel consumption (g/N.s, g/kW.s)
SP	specific power (kW/g/s)

ST	specific thrust (N/kg/s)
T	temperature (K)
TLR	thermal limit ratio (-)
V	velocity (m/s)
$\dot{W}$	work rate (kW)

Greek Letters

η	energy efficiency (%)
ξ	fuel exergy grade function
ψ	exergetic efficiency (%)
Ψ	modified exergetic efficiency (%)

Subscripts

air	air
AC	air compressor
CC	combustion chamber
D	destruction
ED	exhaust duct nozzle
F	inlet streams, fuel
gas	combustion gaseous
GT	gas turbine
GTMS	gas turbine mechanical shaft
in	input
k	the *k*'th component
L	losses
MTJE	micro turbojet engine
out	output, outlet

P	pressure
Pr	product
T	temperature
tot	total
WE	waste exergy
0	dead state conditions

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