

PERFORMANCE ASSESSMENT OF A MEDIUM-SCALE TURBOPROP ENGINE DESIGNED FOR UNMANNED AERIAL VEHICLE (UAV) BASED ON EXERGETIC AND SUSTAINABILITY METRICS

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ABSTRACT

This study presents an exergetic and sustainability analyses to assess the performance of a genuine medium scale turboprop engine (m-TPE) used on the Unmanned Aerial Vehicle (UAV). The exergy efficiency of the engine is obtained to be 17.24% whereas the exergy efficiencies of the compressor, the combustor, the gas generator turbine, the gas generator turbine mechanical shaft, the power turbine, the power turbine mechanical shaft and the exhaust duct are found to be 87.21%, 52.51%, 98.53%, 98.60%, 97.40%, 98.00%, and 94.29%, respectively. From the viewpoint of thermodynamics, the combustor is determined to be the bad factor on the engine performance among the engine components. According to overall engine analysis, the environmental effect factor, exergetic sustainability index, sustainable efficiency factor and ecological effect factor of m-TPE are found to be 4.80, 0.21, 1.21, and 5.80, respectively.

Keywords: *Turboprop Engine, Unmanned Aerial Vehicle, Exergy Analysis, Sustainability Analysis*

INTRODUCTION

Rapid developments and significant progress in aerospace engineering is observed in the present era. Particularly advances in unmanned aerial vehicle (UAV) developments for specific requirements and demands play a determining role. Worldwide researches and studies on UAVs, applicable for military and surveillance purposes, are driving forces of the scientific advancement [1-4]. That yields technological achievements in engine and propulsion system development and integration as well as aerial vehicle design and manufacture.

Turbine engines are widely used devices to generate required thrust for most of the aerial vehicles due to their features. Turbine engines are candidate to serve as propulsion system of UAVs as well as commercial and fighter aircrafts in spite of electromotor known with their characteristics such as light weight, durability, and low cost. Especially military applications require long endurance and flight envelope. If the weight of an armed UAV is considered in company with flight range and envelope, an electromotor is insufficient to power the UAV. For this reason, turbine engines are commonly preferred in military UAVs such as MQ-9 Reaper, RQ-4 Global Hawk, TAI ANKA, General Atomics Avenger and so on [5-11].

It is possible to access many studies on the exergetic, exergoeconomic and sustainability performance evaluations of aircraft gas generator turbine engines [11-35]. At a glance it is clearly understood from these previous texts that both first and second laws of thermodynamics should be employed together to measure the performance of the turbine engines. The first law of thermodynamics manifests the energy conversion phenomena within the evaluated turbine engine. Furthermore using governing equation set of first law is a powerful tool to measure quantity of energy inputs or outputs such as provided energy, generated shaft power, thrust and so on. The second law thermodynamics explains the limitations of the turbine engine according to well-accepted principles asserted by Carnot, Clausius, Kelvin and Planck. So, it is possible to determine design points, optimize and to evaluate improvement feasibility of a turbine engine with the aid of thermodynamics. The combined employment of first and second laws in a performance assessment has a proper name: exergy analysis [36-37].

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An exergetic analysis is a tool to verify the location, size and sources of thermodynamic wastefulness in any energy conversion system or process. This beneficial tool provides data that is impossible to obtain by only energy analysis.

The obtained result from exergy analysis may be employed to improve the efficiency and cost effectiveness of a system while comparing the performance of different systems [38]. In this regard, the exergy analysis of a new designed medium scale turboprop engine (m-TPE) used on the UAV is performed to evaluate the performance of the system. The main goals of the present study are (i) to assess the performance of a new designed medium-scale turboprop engine exergetically, (ii) to estimate the inefficiencies in the components of the engine, and (iii) to determine which component is improved, upgraded or replaced to increase the efficiency of the engine.

ANALYZING METHODOLOGY

Exergy Analysis

Exergy analysis, combination of first and second laws of thermodynamics, shows that exergy waste is a measure of the irreversibility of a process, and that it is proportional to the increase in entropy. Exergy deals with the quality of energy and leads to the property of entropy, which is the measure of disorder in a system. Exergy enables us to determine the best performance of cycles, engines, and devices under operating conditions [39-40].

For any control volume at steady state system, exergy balance relation can be written as [41-42]:

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

where $\dot{E}x$ is the exergy rate. The subscripts F , Pr , D and L denote the total inlet exergy as fuel exergy, the product exergy, the exergy destruction and exergy losses, respectively.

Total waste exergy rate ($\dot{E}x_{WE}$) is determined by:

$$\dot{E}x_{WE} = \sum \dot{E}x_D + \sum \dot{E}x_L \quad (2)$$

Total exergy rate for thermal systems that have not nuclear, magnetism, electricity and surface tension effects can be obtained by [43]:

$$\dot{E}x_{tot} = \dot{m}(\varepsilon_{ph} + \varepsilon_{kn} + \varepsilon_{pt} + \varepsilon_{ch}) \quad (3)$$

here ε_{ph} represents the specific physical exergy, ε_{kn} denotes the kinetic exergy, ε_{pt} symbolizes specific potential exergy, and ε_{ch} stands for chemical exergy, respectively.

The specific physical exergy of air and combustion gases with constant specific heat capacity is estimated from [43-46]:

$$\varepsilon_{ph} = c_{p(T)} \left[T - T_o - T_o \ln \left(\frac{T}{T_o} \right) \right] + RT_o \ln \left(\frac{P}{P_o} \right) \quad (4)$$

The specific kinetic exergy of air and combustion gases is determined from [43-45]:

$$\varepsilon_{kn} = \frac{V^2}{2000} \quad (5)$$

The specific fuel chemical exergy is obtained from [43-45]:

$$\varepsilon_{ch,F} = LHV\xi \tag{6}$$

where ξ symbolizes the exergy grade function for liquid fuels. The ξ of a liquid fuel that have chemical formula as C_aH_b is calculated by [30, 42, 44-45]: ,

$$\xi \cong 1.04224 + 0.011925 \frac{b}{a} - \frac{0.042}{a} \tag{7}$$

For JP-8 jet fuel ($C_{12}H_{23}$), the ξ is obtained to be 1.0616.

Performance Tools for Exergetic and Sustainability Analyses

Exergetic and sustainability performance assessment metrics for aero-engine and its major components were suggested in many former studies [13, 19, 22, 29, 33, 47-50] and some of them are given in Table 1.

Table 1. Exergetic and sustainability performance metrics

<i>Performance metrics</i>	<i>Symbol</i>	<i>Unit</i>	<i>Equations</i>	<i>Eqn.No.</i>
Exergy efficiency	η	(%)	$\eta_k = \frac{\dot{E}x_{Pr}}{\dot{E}x_F} = 1 - \frac{\dot{E}x_D}{\dot{E}x_F}$	(8)
Exergetic improvement potential	$\dot{E}xIP_k$	(kW)	$\dot{E}xIP = (1 - \eta) \dot{E}x_D$	(9)
Relative exergetic improvement potential ratio	α	(%)	$\alpha = \frac{\dot{E}xIP}{\sum \dot{E}xIP_{TPE}}$	(10)
Relative exergy destruction ratio	β	(%)	$\beta = \frac{\dot{E}x_D}{\sum \dot{E}x_{D,TPE}}$	(11)
Relative waste exergy ratio	χ	(%)	$\chi = \frac{\dot{E}x_{WE}}{\sum \dot{E}x_{WE,TPE}}$	(12)
Fuel exergy waste ratio	δ	(%)	$\delta = \frac{\dot{E}x_{WE}}{\sum \dot{E}x_{F,TPE}}$	(13)
Productivity lack ratio	ϕ	(%)	$\phi = \frac{\dot{E}x_{WE}}{\sum \dot{E}x_{Pr,TPE}}$	(14)
Environmental effect factor	φ	(-)	$\varphi = \frac{\delta}{\eta}$	(15)
Exergetic sustainability index	κ	(-)	$\kappa = \frac{1}{\varphi}$	(16)
Sustainable efficiency factor	λ	(-)	$\lambda = \frac{1}{1 - \eta}$	(17)
Ecological effect factor	μ	(-)	$\mu = \frac{\dot{E}x_F}{\dot{E}x_{Pr}} = \frac{1}{\eta}$	(18)

SYSTEM DESCRIPTION AND ASSUMPTIONS

General Engine Description and Technical Data

A turboprop engine (m-TPE) consists of a compressor (AC), a combustor (CC), a gas generator turbine (GT), a gas generator turbine mechanical shaft (GTMS), a free power turbine (PT), a power turbine mechanical shaft (PTMS), an exhaust duct (ED) and propeller. The simplified schematic of the m-TPE is illustrated in Fig 1. In the m-TPE, the ambient air is compressed to a higher pressure by the AC (1-2). The heat addition is supplied in the CC to increase the temperature of the air. The fuel (3) and air (2) are mixed and burned in the combustion process which also raised the enthalpy of working fluid (2-4). The combustion gases (4-5) are expanded throughout the GT to produce the mechanical work that drives the AC via the GTMS (8-9). After that, the combustion gases (5-6) are diluted through the PT to generate the mechanical power that rotates the propeller with PTMS (10-11). Finally, the exiting combustion gases from the PT go through the ED and emits to atmosphere.

The investigated m-TPE was developed for using on the UAV. Under the sea level condition at $T_o=288.15$ K and $P_o=101.325$ kPa, the m-TPE has the following technical data [51]:

- Maximum shaft power: 1000 kW
- Maximum residual power (kinetic energy of exhaust gases):135 kW
- Pressure ratio of compressor: 5.5
- Mass rate of inlet air: 8.66 kg/s
- Mass flow rate of JP-8 jet fuel: 0.145 kg/s.
- Air-fuel ratio: 59.72
- Pressure drop in the combustor: 5%
- Gas generator turbine inlet temperature: 1058.15 K.
- Gas generator turbine outlet temperature: 890.35 K
- Pressure ratio of gas generator turbine: 2.68
- Power turbine outlet temperature: 799.50 K
- Pressure ratio of power turbine: 1.8
- Exhaust outlet temperature and pressure: 797.25 K and 107.55 kPa
- Velocity of exhaust gases: 175.5 m/s

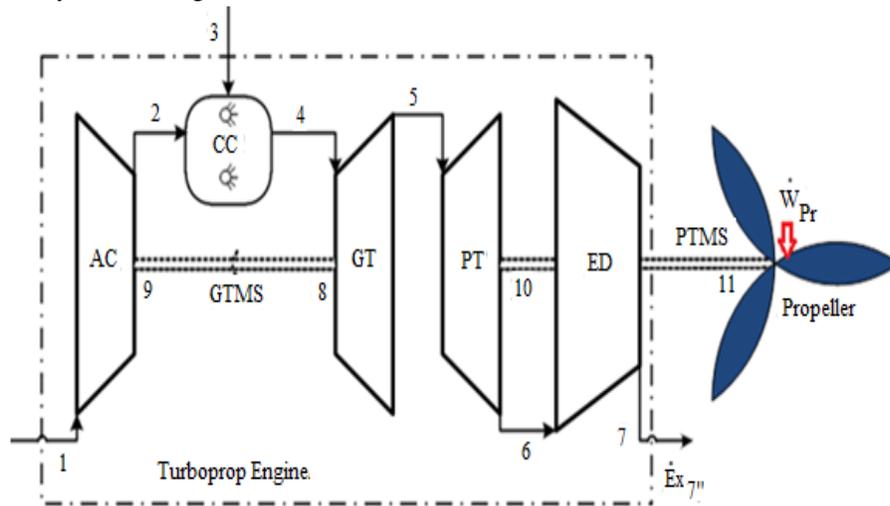


Figure 1. A simplified schematic of the investigated m-TPE

Assumptions

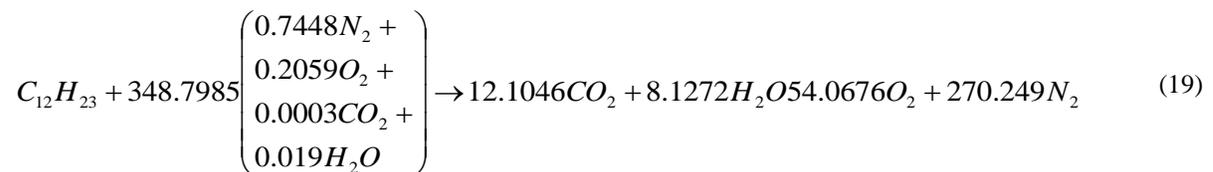
The flowing postulates are made are for this study:

- The m-TPE run in a steady-state and steady flow.
- The air and combustion gases were assumed as an ideal-gas mixture.
- The combustion reaction was complete.

- The fuel inletting into combustor was the JP-8 fuel.
- The chemical formula of JP-8 was presumed $C_{12}H_{23}$.
- The lower heating value of JP-8 fuel was to be 42,800 kJ/kg.
- The compressor, the gas generator turbine and the power turbine were taken into consideration as adiabatic.
- The changes in the kinetic energy and exergy rates, the potential energy and exergy rates within the engine were assumed to be negligible.
- The air mass flow velocity entering the compressor was zero hence the engine test was made in a static condition at test cell.
- The cooling air mass rate was ignored.
- The environmental state was taken to be 288.15 K and 101.33 kPa, respectively.

Specific Heat Capacity of Air and Combustion Gases

The pressured air at compressor outlet goes into the combustor and mixes by sprayed jet fuel. The mixed air-jet fuel is ignited by high energy igniter and burning starts in the combustor. For stable burning, the air-fuel ratio must be at convenient level. The air- fuel ratio in the combustor is always higher than stoichiometric ratio for completed fuel burning and decreasing the combustion gases temperature in inlet of the gas generator turbine. The combustion reaction relation for JP-8 jet fuel is written as following:



After combustion reaction, the mass compositions of combustion gases are obtained to be 5.24% CO_2 , 3.21% H_2O , 17.03% O_2 and 74.51% N_2 . The universal gas constant (R_{gas}) of the exhaust gases is obtained to be 0.29136 kJ/kgK. The specific heat capacity of exhaust gases ($c_{p,cg}$) is calculated by [52]:

$$c_{p,cg}(T) = 0.98836 + \frac{0.01138}{10^2} T + \frac{0.01540}{10^5} T^2 - \frac{0.06695}{10^9} T^3 \quad (20)$$

The specific heat capacity of air is accounted by [19, 22, 30, 41, 43-45]:

$$c_{p,a}(T) = 1.04841 - \left(\frac{3.83719T}{10^4} \right) + \left(\frac{9.45378T^2}{10^7} \right) - \left(\frac{5.49031T^3}{10^{10}} \right) + \left(\frac{7.92981T^4}{10^{14}} \right) \quad (21)$$

Here T is temperature in Kelvin unit.

Exergy Balance Relations

The exergy balance relations in this study are written in accordance with the F(fuel)-Pr (Product) rule [40]. The exergetic balance relations for the m-TPE and its major components are given as following;

For compressor (AC):

$$\dot{E}x_{D,AC} = \dot{W}_9 - (\dot{E}x_2 - \dot{E}x_1) \quad (22)$$

For combustor (CC):

$$\dot{E}x_{D,CC} = \dot{E}x_3 - (\dot{E}x_4 - \dot{E}x_2) \quad (23)$$

For gas generator turbine (GT):

$$\dot{E}x_{D,GT} = (\dot{E}x_4 - \dot{E}x_5) - \dot{W}_8 \quad (24)$$

For gas generator turbine mechanical shaft (GTMS):

$$\dot{E}x_{D,GTMS} = \dot{W}_8 - \dot{W}_9 \quad (25)$$

For power turbine (PT):

$$\dot{E}x_{D,PT} = (\dot{E}x_5 - \dot{E}x_6) - \dot{W}_{10} \quad (26)$$

For power turbine mechanical shaft (PTMS):

$$\dot{E}x_{D,PTMS} = \dot{W}_{10} - \dot{W}_{11} \quad (27)$$

For exhaust duct (ED):

$$\dot{E}x_{D,ED} = (\dot{E}x_6 - \dot{E}x_7) \quad (28)$$

Total exergy destruction rates can be written as:

$$\sum \dot{E}x_{D,TPE} = \dot{E}x_{D,AC} + \dot{E}x_{D,CC} + \dot{E}x_{D,GT} + \dot{E}x_{D,GTMS} + \dot{E}x_{D,PT} + \dot{E}x_{D,PTMS} + \dot{E}x_{D,ED} \quad (29)$$

On the other hand; total exergy losses rates are estimated by:

$$\sum \dot{E}x_{L,TPE} = (\dot{E}x_1 + \dot{E}x_3)_{TPE} - \sum \dot{E}x_{Pr,TPE} - \sum \dot{E}x_{D,TPE} \quad (30)$$

$$\sum \dot{E}x_{Pr,TPE} = Ex_{7,TPE}^{KN} + \dot{W}_{11,TPE} \quad (31)$$

RESULTS AND DISCUSSION

The thermodynamic cycle data is given in Table 2 for investigated m-TPE. Using data in Table 2, the exergy rates, exergetic and sustainability performance indicators of the m-TPE and its major subcomponents are obtained and listed in Table 3 and 4.

Table 2. The exergy rate and other thermodynamic properties of the m-TPE at maximum operation power

State no.	Fluid type/work	$P(kPa)$	$T(K)$	$\dot{m}(kgs^{-1})$	$c_p(kJ(kg-K)^{-1})$	$\dot{E}(kW)$	$\dot{E}_x(kW)$
0	Air	101.33	288.15	0.00	1.00375	0.00	0.00
1	Air	101.33	288.15	8.66	1.00375	0.00	0.00
2	Air	557.29	498.15	8.66	1.02887	1933.80	1686.54
3	Fuel	250.09	298.15	0.15	1.94700	6206.00	6588.29
4	Combustion gases	529.42	1058.15	8.81	1.12912	7973.32	5145.93
5	Combustion gases	197.55	890.35	8.81	1.09174	6012.04	3155.43
6	Combustion gases	109.75	799.50	8.81	1.07080	4991.30	2107.48
7	Combustion gases	107.55	797.25	8.81	1.07027	4966.43	1987.16
8	Mechanical power					1961.28	1961.28
9	Mechanical power					1933.80	1933.80
10	Mechanical power					1020.74	1020.74
11	Mechanical power					1000.33	1000.33
7''	Residual kinetic exergy					135.60	135.60

Table 3. The exergy rate, exergy efficiency and exergetic improvement potential of the m-TPE at maximum operation power

Components	$\dot{E}_{x_f}(kW)$	$\dot{E}_{x_{Pr}}(kW)$	$\dot{E}_{x_D}(kW)$	$\dot{E}_{x_L}(kW)$	$\eta(\%)$	$\dot{E}_{xIP}(kW)$
AC	1933.80	1686.54	247.26		87.21	31.62
CC	6588.29	3459.39	3128.90		52.51	1485.98
GT	1990.50	1961.28	29.22		98.53	0.43
GTMS	1961.28	1933.80	27.48		98.60	0.38
PT	1047.95	1020.74	27.20		97.40	0.71
PTMS	1020.74	1000.33	20.41		98.00	0.41
ED	2107.48	1987.16	120.32		94.29	6.87
$\sum \dot{E}_{x_D}$			3600.80			
$\sum \dot{E}_{x_L}$				1851.56		
$\sum \dot{E}_{xIP}$						1526.39
Shaft power (\dot{W}_{11})		1000.33				
Kinetic exergy (\dot{E}_{x_7})		135.60				
The m-TPE	6588.29	1135.93	3600.80	1851.56	17.24	

The engine produces 1135.93 kW (100.33 kW-shaft power and 135.60 kW- kinetic energy rate of exhaust gases) for the maximum running mode at the sea level when it expends 6588.29 kW-exergy rate of JP-8 fuel. The exergetic efficiency (η) of the m-TPE is obtained to be 17.24%. On the other hand, total waste exergy flow is estimated to be 5452.36 kW. The exergy destruction rate portion of the waste exergy is calculated to be 3600.8 kW while the exergy losses portion is accounted to be 1851.56 kW. The percent of product exergy rate, exergy destruction rate and exergy losses rate is illustrated in Figure 2. The percent of product exergy rate, exergy destruction rate and exergy losses rate is illustrated in Fig.2. According to the Fig. 2, 54.65% of provided exergetic fuel rate is destructed in the end of the irreversible processes whereas 28.52% of fuel exergy rate is emitted into environment by exhaust gases as exergy losses rate of m-TPE.



Figure 2. Breakdown of the fuel exergy rate into parts

On the other hand, the fuel exergy waste ratio (δ), productivity lack ratio (ϕ), environmental effect factor (γ), exergetic sustainability index (κ), sustainable efficiency factor (λ) and ecological effect factor (μ) of the m-TPE is obtained to be 82.76%, 479.99%, 4.80, 0.21, 1.21 and 5.80, respectively according to the sustainability analysis. In addition to Table 3 and 4, Figure 3 is plotted for a better understanding of fuel, product and destruction exergy rates of each engine component individually. As an idea to support exergy efficiency of each product, the fuel exergy rate of gas generator turbine, power turbine and turbine shafts are considerably converted into product exergy rate.

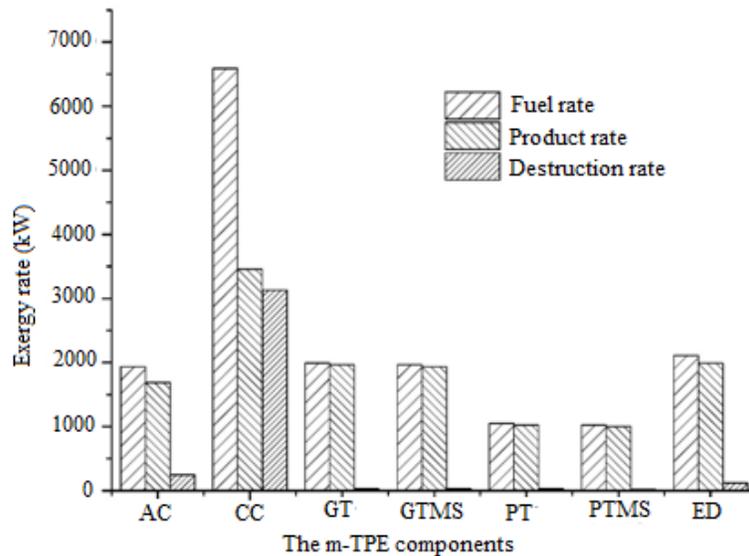


Figure 3. Exergy rate variation of engine components

On the other hand, product and destruction rates of the combustor are roughly equal and so close to each other. That implication is another indicator of the exergy efficiency variation of engine components demonstrated in Figure 4. The exergy efficiencies of the compressor, the combustor, the gas generator turbine, the gas generator turbine mechanical shaft, the power turbine, the power turbine mechanical shaft and the exhaust duct are obtained to be 87.21%, 52.51%, 98.53%, 98.60%, 97.40%, 98.00%, and 94.29%, respectively.

Table 4. The exergetic and sustainability performance metrics of the m-TPE at maximum operation power

Components	α (%)	β (%)	χ (%)	δ (%)	ϕ (%)	φ (-)	κ (-)	λ (-)	μ (-)
AC	2.07	6.87	4.535	3.75	21.77	0.043	23.238	7.821	1.147
CC	97.35	86.89	57.386	47.49	275.45	0.904	1.106	2.106	1.904
GT	0.03	0.81	0.536	0.44	2.57	0.005	222.138	68.114	1.015
GTMS	0.03	0.76	0.504	0.42	2.42	0.004	236.432	71.384	1.014
PT	0.05	0.76	0.499	0.41	2.39	0.004	235.894	38.522	1.027
PTMS	0.03	0.57	0.374	0.31	1.80	0.003	316.266	50.000	1.020
ED	0.45	3.34	2.207	1.83	10.59	0.019	51.629	17.515	1.061
$\sum \dot{E}x_D$			66.041	54.66	316.99				
$\sum \dot{E}x_L$			33.959	28.10	163.00				
$\sum \dot{E}x_{IP}$									
The m-TPE				82.76	479.99	4.800	0.208	1,208	5.800

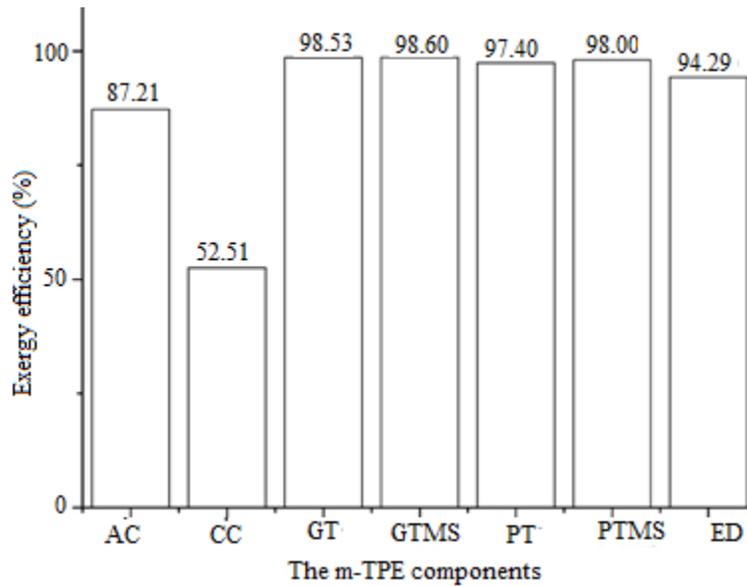


Figure 4. Exergy efficiency variation of engine components

Between the components, the highest exergy destruction occurs in the combustor with the rate of 1485.98 kW that is to be 86.89% of the total exergy destruction rate in the engine. According to Figures 3 and 4, the combustor is the bad factor for engine performance from the thermodynamic viewpoint.

Figures 5 and 6 indicate exergetic performance metrics of each engine component. As shown in Figure 5, relative improvement potential ratio of the engines are found to be 6.86%, 86.89%, 0.81%, 0.76%, 0.75%, 0.56%, and 3.34% whereas the relative exergy destruction ratio is calculated to be 2.07%, 97.35%, 0.02%, 0.02%, 0.04%, 0.02%, and 0.45% for the compressor, the combustor, the gas generator turbine, the gas generator turbine mechanical shaft, the power turbine, the power turbine mechanical shaft and the exhaust duct respectively. This result corroborates the assertion of combustor to be the most inefficient component with a high exergy destruction rate and improvement potential among other engine components.

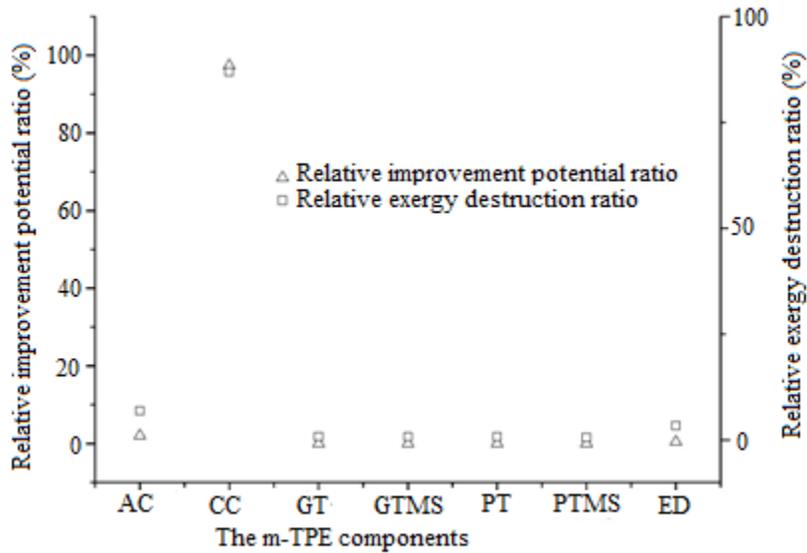


Figure 5. Relative improvement potential and relative exergy destruction ratio variation of engine components

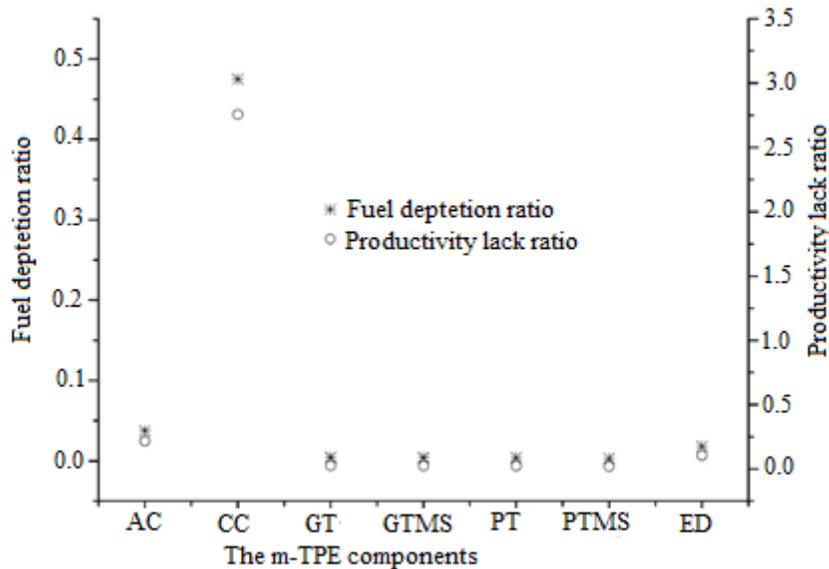


Figure 6. Fuel depletion ratio and productivity lack ratio variation of engine components

Figure 6 is another expression of Figure 3. Herein, fuel depletion ratio reveals the destructed amount of the fuel exergy rate for each component. In this manner, the combustor has the highest fuel depletion rate with value of 0.47 whereas the power turbine mechanical shaft has the lowest fuel depletion ratio. Productivity lack ratio is an indicator of destructed exergy amount compared to product exergy rate. From this point of view, fuel depletion ratio and productivity lack ratio characteristics of engine components are similar.

At the same time, the environmental and sustainability performance indicators of the m-TPE and its components are given in Table 4. The environmental effect factor and ecological effect factor of engine components are illustrated in Figure 7 while the exergetic sustainability index and sustainable efficiency factor of engine components are shown in Figure 8. Figure 7 and 8 indicate that the combustor between the engine components has the worst values of environmental effect factor, ecological effect factor, exergetic sustainability index and sustainable efficiency factor.

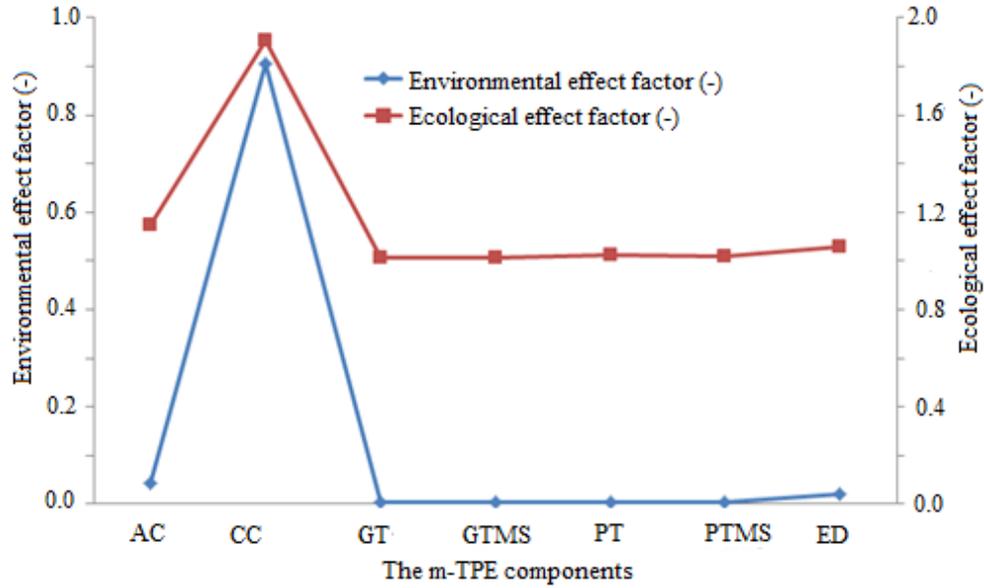


Figure 7. The environmental effect factor and ecological effect factor of engine components

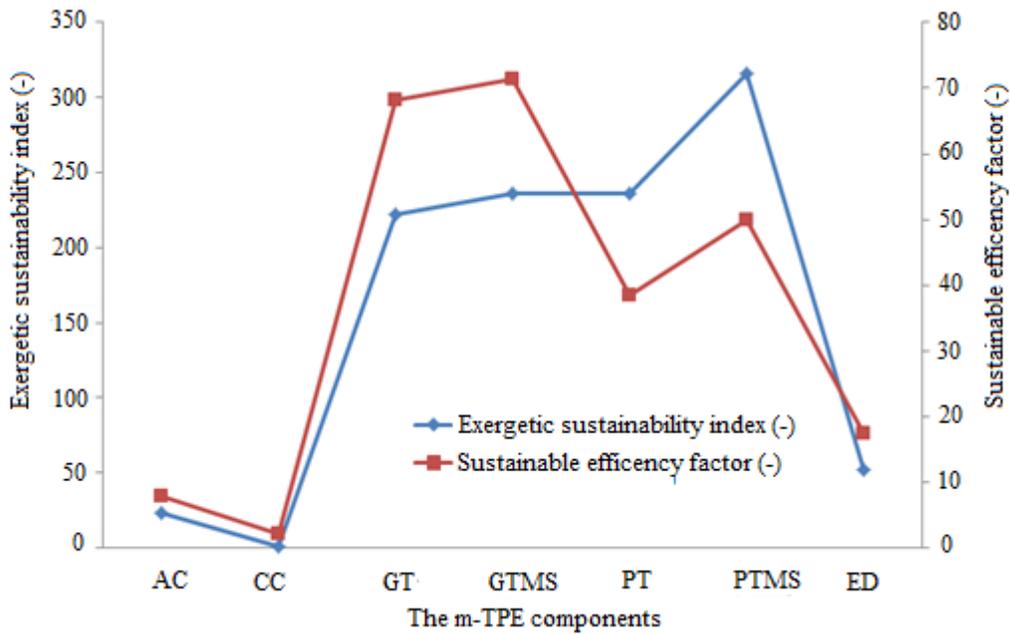


Figure 8. The exergetic sustainability index and sustainable efficiency factor of engine components.

As a result, the combustor has the maximum relative waste exergy ratio (χ), fuel exergy waste ratio (δ), productivity lack ratio (ϕ), environmental effect factor (φ) and ecological effect factor (μ) with 57.39%, 47.49%, 275.45%, 0.90 and 1.90 while it has the minimum exergetic sustainability index ($\kappa = 1.11$) and sustainable efficiency factor ($\lambda = 2.11$).

The results of this study clearly point out that the combustor is the bad component for m-TPE's performance from the thermodynamic viewpoint. The combustor, in which the combustion process occurred, has the lowest exergy efficiency value, and the highest values of the other thermodynamic parameters due to the combustion

wastefulness. Fuel burning is a very complex process and it is largely thermodynamically irreversible process. To rise up and improve the exergetic and sustainability performance of the m-TPE, the designer must focus on the combustor component to improve or develop its properties thermodynamically.

CONCLUSION

This study presents an exergy based analysis to assess the exergetic and sustainability characteristics of a genuine design medium scale turboprop engine (m-TPE) developed for UAVs. The main noteworthy outcomes of this study are given as follows:

- The exergetic efficiency value (η) of the m-TPE is obtained to be 17.24% while the fuel exergy waste ratio (δ) is computed to be 82.76%. For increasing the exergy efficiency of the engine, the exergy waste ratio should be decreased. On the other hand, the exergy destruction rate of the combustion chamber has to be minimized in order to reduce the waste exergy rate of engine.
- The productivity lack ratio (ϕ) is estimated to be 479.99%. Higher value of productivity lack ratio shows that the engine either generates low product rate or has higher waste exergy rate.
- The environmental effect factor (γ) and ecological effect factor (μ) indicate that how engine running affects the environment and ecology of the world. Because higher values are the bad effect factor for environment and ecology, the low values are desired. The environmental effect factor (γ) and ecological effect factor (μ) are calculated to be 4.80 and 5.80 for the investigated engine.
- The exergetic sustainability index and sustainable efficiency factor (λ) of the m-TPE are estimated to be 0.21 and 1.21, respectively.
- Between engine major components, the combustor has the bad exergetic and sustainability metrics and it decreases the exergetic and sustainability performances from the thermodynamic viewpoint
- The results of this study indicate that the designer must concentrate on the combustor component to become better or advance its thermodynamic attributes.

NOMENCLATURE

AC	Air compressor
c_p	Specific heat at constant pressure, kJ /kgK
CC	Combustion chamber
E	Energy, kW
ED	Exhaust duct
\dot{E}_x	Exerget rate, kW
\dot{E}_{xIP}	Exergetic improvement potential rate, kW
GT	Gas turbine
GTMS	Gas turbine mechanical shaft
m-TPE	Medium scale turboprop engine
LHV	Lower heating value, kJ/kg
P	Pressure, kPa
PT	Power turbine
PTMS	Power turbine mechanical shaft
R	Relative gas constant, kJ/kgK
T	Temperature, K
UAV	Unmanned aerial vehicle
V	Velocity, m/s
W	Work rate, kW

Greek symbols

α	Relative exergetic improvement potential ratio, %
β	Relative exergy destruction ratio, %
χ	Relative waste exergy destruction ratio, %
δ	Fuel exergy waste ratio, %
ε	Specific exergy kJ/kg
ϕ	Productivity lack ratio, %
φ	Environmental effect factor, -
η	Exergy efficiency, %
κ	Exergetic sustainability index, -
λ	Sustainable efficiency factor, -
μ	Ecological effect factor, -
ξ	Fuel exergy grade function, -

Subscripts

a	Air
AC	Air compressor
CC	Combustion chamber
cg	Combustion gases
ch	Chemical
D	Exergy destruction
ED	Exhaust duct
F	Fuel
GT	Gas turbine
GTMS	Gas turbine mechanical shaft
k	k'th component
kn	kinetic
L	Exergy losses
TPE	Turboprop engine
P	Pressure
ph	Physical
Pr	Product
pt	Potential
P	Pressure
PT	Power turbine
PTMS	Power turbine mechanical shaft
T	Temperature
WE	Waste exergy

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