A CRITICAL REVIEW OF EXERGY STUDIES ON JET ENGINES

Meryem Gizem SÜRER[1], Hüseyin Turan ARAT[2*]
[1]Depertmant of Mechanical Engineering, İskenderun Technical University, Hatay/TURKEY
[2]Depertmant of Mechatronics Engineering, İskenderun Technical University, Hatay/TURKEY
Corresponding author: Hüseyin Turan ARAT, e-mail: hturan.arat@iste.edu.tr

REFERENCE NO

EXGY-01

Keywords:
Exergy
Jet Engines
Aviation
Availability
Efficiency

ABSTRACT

Because of increased industrialization and energy demand, energy and exergy studies are becoming increasingly important in all materials that produce and use energy. Supply and demand unbalancing in energy production and consumption necessitates effective usage of energy. Exergy analyzes; has become one of the most important tips and solution partners that engineering practitioners have been mindful of in explaining the availability of energy. In aviation sector; jet engines components are playing a key role for energy production, transmit and distribution. In this critical mini review, exergy analyses of jet engines (gas turbines) used in the air vehicles are given comparatively. The studies that emphasize the importance of energy and exergy analysis and the more effective usage of energy in jet engines are compiled. In this mini but new review approach, the exergy of jet engines are added to the literature with reviewed version.

1. INTRODUCTION

In the aviation sector, energy analysts have researched for ways to use the energy effectively for a long time, as the airway transport has growing more and more in addition to the risk of depletion of jet fuels and seriously increasing harmful gas emissions. Thus, the investigation of how these critical important jet engines have use energy has attracted a great deal of interest from energy analysts, which has led to numerous benefits to the industry. Jet engines which have many different types as turbojet, turboprop, turbofan, turbo shaft, propfan and advanced ducted fan [1] and operate in an open cycle based on the Brayton cycle to produce thrust [2], are very complicated systems composed of a large number of components [3-4].

The quantity and quality of the energy are the important factors to consider for efficiently usage of energy [4- 5]. While the first law of thermodynamics widely used in energy analysis takes into account the quantity of energy, the second law of thermodynamics, which is commonly used in exergy analysis and includes the concepts of reversibility / irreversibility, deals with the quality of energy [6-8]. Exergy is defined as the highest theoretical work that a process can achieve while it comes to balance with the environment as basis of mechanical, thermal, and chemical [1, 4 -6, 9]. In aviation sector, the main purpose of an exergy analysis is to improve engine performance by determining the magnitude and location of the exergy destruction which is originated by entropy production [9]. In this way, designers can modify the energy system by identifying the component with the highest exergy destruction [6]. With exergy analysis, thermal systems also can be optimized in issue with regard to environmental, economics and sustainability [1]. As a result, it is possible to use energy more efficiently in many directions thanks to exergy analysis in gas turbines and its components [8].

In this study, evaluation of papers which related with exergy analysis applied to jet engines has been given comparatively. The general purpose of this study is to reach the answer of these questions like; how the other exergy studies are prepared and examined, which formulas or mathematical approaches are selected for the exergy analysis, which exergetic efficiency and exergy destructions are found for which type of engine?

2. THERMODYNAMICAL METHODS ON ENERGY AND EXERGY ANALYSIS

2.1 Energy Analysis

For a steady state control volume, the mass balance equation and the general energy balance can be written as equations 1 and 2 respectively [8-12].

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \qquad (1)$$

$$\dot{Q} - \dot{W} + \sum \dot{m}_{in} [h_{in} + (V_{in}^2 /2) + gz_{in}] - \sum \dot{m}_{out} [h_{out} + (V_{out}^2/2) + gz_{out}] = 0 \qquad (2)$$

Where $\dot{m}$ is the mass flow rate, $\dot{Q}$ is the net heat transfer rate to the control volume, $\dot{W}$ is net work production, h is the specific enthalpy, V is the velocity, g is gravitational acceleration, and z is the elevation. However, the lower symbols represent the in and out inputs and outputs, respectively.

The mass balance equation and the general energy balance applied to the jet engine components are given in Table 1.

2.2. Exergy Analysis

When nuclear, magnetic, electric, and surface tension effects is not involved [13-15], generally exergy analysis approach divides into four component such as specific physical exergy (e_{ph}), specific chemical exergy (e_{ch}) ,specific kinetic exergy (e_{kn}), specific potential exergy (e_{pt}) [14-20] :

$$e_t = e_{ph} + e_{ch} + e_{kn} + e_{pt} \qquad (3)$$

Where e_t denotes total specific exergy.

Physical exergy is normally arises from temperature, pressure, kinetic or potential energy differences [21] and can be expressed as follows [7-11]:

$$e_{ph} = (h-h_0)-T_0(s-s_0) \qquad (4.a)$$

For perfect gases [1, 7, 10-11]:

$$e_{ph} = c_p(T-T_0)-T_0(C_p \ ln\frac{T}{T_0} - R \ ln \frac{P}{P_0}) \qquad (4.b)$$

Where s is entropy, T is temperature, c_p is constant pressure specific heat, R is gas constant and the subscript zero indicates properties at the restricted dead state of P_0 and T_0.

The chemical exergy quantity varies due to the used difference fuel [1] and chemical exergy of gas mixtures and liquid fuel is formulated as follows respectively [1,9-10,35]:

$$e_{ch,mix} = \sum x_i e_{i,ch} + RT_0 \sum x_i ln x_i \qquad (5.a)$$

$$e_{ch,\, fuel} = LHV [\, 1.0401 + 0.1728\frac{h}{c} + 0.0432\frac{o}{c} + 0.2169\frac{s}{c}\,(\, 1-2.0628\frac{h}{c})] \qquad (5.b)$$

Where h, c, o and s symbolize the fuel ingredients of hydrogen, carbon, oxygen and sulphur atomic fractions.

As the potential exergy is neglected due to no significant height difference between the inlet and the outlet of the engine, kinetic energy is also neglected in many studies [1, 4]. Exergy values of kinetic and potential are the same to those of the energy values [22] and formulated as follows [2]:

$$e_{kn} = \frac{V^2}{2} \qquad e_{pt} = gh \qquad (6)$$

As a result, total exergy rates [$\dot{E}$] can be determined as [2]:

$$\dot{E}x = \dot{M}\, e_t \qquad (7)$$

In aircraft engines components, used general exergy balance is written by [6-7, expressed detailed 8-10] and listed table 1.

$$\sum \dot{E}x_{in} - \sum \dot{E}x_{out} - \sum \dot{E}x_{dest} = 0 \qquad (8.a)$$

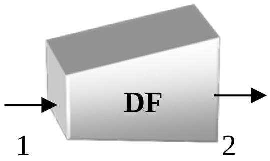
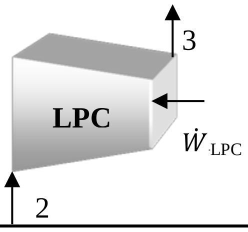
$$\dot{E}x_{heat} - \dot{E}x_{work} + \dot{E}x_{mass,\, in} - \dot{E}x_{mass,\, out} - \dot{E}x_{dest} = 0 \qquad (8.b)$$

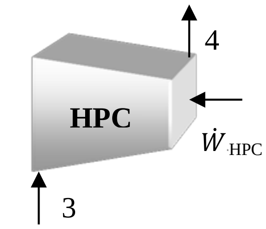
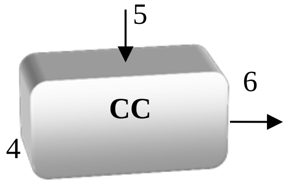
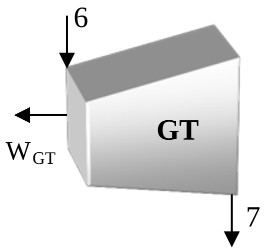
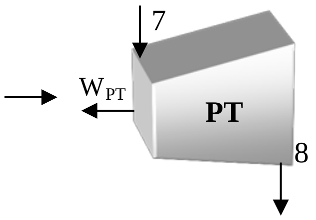
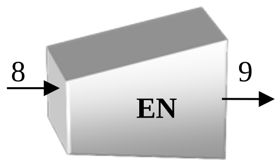
$$\dot{E}x_{heat} = \sum (1-(\frac{T_0}{T_j}))\dot{Q}_j \qquad (9)$$

$$\dot{E}x_{work} = \dot{W} \quad (10)$$

Where $\dot{Q}_j$ is the net heat transfer from the limit of the control volume to the T_J temperature, $\dot{W}$ is net work transfer, $\dot{E}x$ is the amount of exergy at input and output, $\dot{E}x_{dest}$ is amount of exergy destruction.

Table .1 Energy and exergy balance for conventional jet engine components (engine components are adiabatic, air and exhaust gas are ideal, kinetic and potential energy/exergy are negligible, and datas are gathered from [2,6,9,23])

Engine components	Energy Balance	Exergy balance	Exergy efficiency
	$\dot{m}_1 = \dot{m}_2$	$\dot{E}_1 - \dot{E}_2 = \dot{E}_{D,D}$	$\eta_{ex} = \frac{\dot{E}_2}{\dot{E}_1}$
	$\dot{W}_{LPC} = \dot{m}_{air}\, c_{p,air}\, (T_3 - T_2)$ $\dot{m}_2 = \dot{m}_3$	$\dot{W}_{LPC} + \dot{E}_2 - \dot{E}_3 = \dot{E}_{D,LPC}$	$\eta_{ex} = \frac{\dot{E}_3 - \dot{E}_2}{\dot{W}_{LPC}}$

	$\dot W_{HPC} = \dot m_{air} c_{p,air} (T_4 - T_3)$ $\dot m_3 = \dot m_4$	$\dot W_{HPC} + \dot E_3 - \dot E_4 = \dot E_{D,HPC}$	$\eta_{ex} = \frac{\dot E_4 - \dot E_3}{\dot W_{HPC}}$
	$m_4 h_4 + m_5 LHV = m_6 h_6 + (1 - \eta_{CC}) m_5 LHV$ $\dot m_4 + \dot m_5 = \dot m_6$	$\dot E_4 + \dot E_5 - \dot E_6 = \dot E_{D,cc}$	$\eta_{ex} = \frac{\dot E_6}{\dot E_4 + \dot E_5}$
	$\dot W_{GT} = \dot m_{exh} c_{p,exh} (T_7 - T_6)$ $\dot m_6 = \dot m_7$	$\dot E_6 - \dot E_7 - \dot W_{GGT} = \dot E_{D,GT}$	$\eta_{ex} = \frac{\dot W_{GT}}{\dot E_6 - \dot E_7}$
	$\dot W_{PT} = \dot m_{exh} c_{p,exh} (T_7 - T_6)$ $\dot m_7 = \dot m_8$	$\dot E_6 - \dot E_8 - \dot W_{PT} = \dot E_{D,PT}$	$\eta_{ex} = \frac{\dot W_{PT}}{\dot E_7 - \dot E_8}$
	$\dot m_8 = \dot m_9$	$\dot E_7 - \dot E_8 = \dot E_{D,EN}$	$\eta_{ex} = \frac{\dot E_9}{\dot E_8}$

Exergy efficiency is one of the important parameter and is calculated as follow [7]:

$$\eta_{ex} = \frac{\dot E_{out}}{\dot E_{in}} = 1 - \frac{\dot Ex_{dest}}{\dot Ex_{in}} \quad (11)$$

In addition to the exergy efficiency, there are different parameters for thermodynamic evaluation of the system. These parameters are explained in [6, 9] below:

$$\chi_k = \frac{\dot Ex_{D,k}}{\dot Ex_{D,tot}} \quad (12)$$

Where χ_k donates relative exergy destruction, $\dot Ex_{D,k}$ donates amount of exergy destruction of k_{th} component of the system, $\dot Ex_{D,tot}$ denotes amount of exergy destruction of the entire system.

$$\delta_k = \frac{\dot Ex_{D,k}}{\dot Ex_{fuel,total}} \quad (13)$$

Where δ_k denotes fuel depletion ratio, $\dot Ex_{fuel,total}$ denotes total fuel exergy of the entire system.

$$\xi = \frac{\dot{E}x_{D,k}}{\dot{E}x_{product,total}} \quad (14)$$

Where ξ denotes productivity loss and expresses how much of the exergy of the product is lost as destruction.

$$I\dot{P}_k = (1-\eta_{ex})\,(\dot{E}x_{in} - \dot{E}x_{out}) \quad (15)$$

Where $I\dot{P}_k$ denotes exergetic improvement potential and determines that how much better system can be improved.

However, exergetic sustainability indicators like exergy destruction factor (EDF), waste exergy ratio (WER), environmental effect factor (EEF), exergetic sustainability index (ESI) are defined and formulated by [24-25].

3. EXERGY STUDIES ON AIRCRAFT JET ENGINE

In this section, exergy studies applied to jet engines were given in historical order from the first available work to until today. Detailed information on these studies is shown in table 2. In all studies, while exergy analysis was applied to jet engine, the following assumptions were accepted:

●Engine was operated in steady state.

●The combustion reaction was complete.

●Air and exhaust gases were ideal gases.

●Potential exergy and chemical exergy except in CC, was calculated as zero.

While studies done by [2-3,6, 8-11, 13-20,23,26-30 ,32-33] have been accepted that engine components were adiabatic, in the study done by [24] have been accepted that turbine and nozzle were non-adiabatic and in the study done by [22] have been accepted that turbine was non-adiabatic. Additionally, ref [2,6,8-11,14-16,18-29,30-33] have accepted that the air entered engine composed of 77.48% N_2, 20.59% O_2, 0.03% CO_2 and 1.90% H_2O, ref [13,20] have accepted that the air entered engine composed of 74.48% N_2, 20.59% O_2, 0.03% CO_2 and 1.90% H_2O, ref [17,23] have accepted that 75.67% N_2, 20.35% O_2, 0.0345% CO_2 and 3.03 % H_2O, ref [34] have accepted that 79.67% N_2, 18.77% O_2, 1.53% H_2O, and 0.03% CO_2 and ref [3, 22, 24-29,35] haven't specified air composition. Studies done by [6, 8-11, 13-20, 22-24, 27, 30-31] assume that the velocity of air mass flow entering the engine have taken zero. However, studies done by [6, 9-11, 13-20, 22-23,27,30-31] have assumed that the changes in the kinetic energy were negligible.

4. CONCLUSION

The following conclusions can be made as a result of the studies examined:

●Combustor chamber exit temperature and pressure ratio of engine has important effect on CC by increasing exergy efficiency.

●If there is no afterburner, the CC has the greatest exergy destruction and the minimum exergy efficiency value due to combustion process is highly thermodynamically irreversible process. If there is afterburner, the biggest exergy destruction and the smallest exergy efficiency are observed in this component and the CC follows this value.

●As the partial load increases, the engine's exergy destruction increases.

●As altitude increase, the efficiency of engine decrease.

● When velocity is reduce, the exergy efficiencies the of all components decrease.

Table 2. Exergy studies applied to jet engines in historical order from newest to oldest accessible works

Ref	Year	Engine/fuel type	Exergy analysis condition	Exergy analysis results
[8]	2017	Turbojet/JP8 ($C_{10.9}H_{20.9}$)	Exergy analysis was applied to combustor by changing overall pressure ratio, combustor exit temperature and combustor pressure ratio. ●The ambient temperature and pressure was 288 K and 101.3 kPa.	●The effect of combustor exit temperature increased from 1,100 K to 1,800 K was determined as exergy efficiency increased %15.8. ●As overall pressure of engine increased from 4.0 to 7.0, exergy efficiency increased 4.5 %. ●Pressure dropped from 3.0 to 10.0 caused decreasing of %1.4 exergy efficiency in combustor.

[24]	2017	Turbojet/ kerosene	Four part loads were selected as operating condition for exergy analysis. These were part load-1/2/3/4 and their percentage ratios are given as 29%, 37%, 42%, 48%, respectively. ●The ambient temperature and the pressure were 288.15 K and 102 kPa.	●In CC, maximum exergy destructions was observed as 48.96 kW, 57.14 kW, 67.93 kW and 74.38 kW for four loadings, respectively. ●In partial load-4, the maximum kinetic exergy and exhaust loss were calculated as 3.06 kW and 22.7 kW, respectively, ●The maximum and minimum exergy efficiencies were observed as 7.8% at part load 3, 52% at part load 1, respectively. ●The minimum WER, the maximum EDF, the minimum EEF , the maximum ESI were calculated as 0.9 at part load-4 , 0.938 at part load-1, 12.03 at part load-3, 0.083 at part load-3, respectively.
[13]	2017	Turbofan/ JP8 ($C_{12}H_{23}$)	The Maximum Take-Off Power (MTOP) operation mode and the Take-Off Running Power (TORP) were chosen for implementing exergy analysis at the seal level. ●The ambient temperature and the pressure were 288.15 K and 101.33 kPa.	●The maximum exergy destruction rate was determined as 47469.39 kW with 63.86% exergetic efficiency in CC. ●The exergy efficiency of TFE is calculated as 26.81% for the MTOP mode and 20.54% for the TORP mode. ●The exergy efficiency, waste exergy ratio, improvable exergy potential ratio, productivity lack ratio, environmental effect factor were calculated to be 0.268, 0.732, 0.536, 2.730, 3.495, for the MTOP operation modes while they were obtained to 0.205, 0.795,0.631, 3.869, 4,563 for the TORP operation modes.
[14]	2017	Turbojet with afterburner/ JP8 ($C_{12}H_{23}$)	Exergy analysis was applied to turbojet in military (MIL) mode (without afterburner) and AB mode (with afterburner), respectively. ●The ambient temperature and the pressure were 288.15 K and 101.33 kPa.	●The exergy efficiency of the TJE was determined as 39.41% for MIL mode and 17.9% for AB mode. ●The exergetic efficiencies of the LPC, LPT, CC, HPT, LPT, HPTMS and LPTMS were calculated to be 87.23%, 86.77%, 70.82%, 98.21%, 97.88%, 98.5%, and 98.5% at both two mode. Only, exergetic efficiency of the ABED was obtained as 49.41% at AB mode and 91.91% at MIL mode. ●CC, in which highest exergy destruction took place with the rate of 20878.64 kW, had the maximum relative exergy destruction ratio with 76.76% during MIL operation. However, the highest exergy destruction with 85176.21 kW and the maximum relative exergy destruction ratio with 77.05% took place in afterburner exhaust duct for AB operation.
[10]	2017	Turboshaft/ Jet A-1 ($C_{12}H_{23}$)	Four different load values (284 N$m for test #1, 436 N$m for test #2, 547 N$m for test #3 and 579 N$m for test #4) were selected for exergy analysis ● The bleed airflow used to pressurize the turbine bearings section was assumed to be 2% of the total airflow entering the engine. ●The ambient temperature and the pressure were 288.15K and 92kPa.	●The exergy destruction rates of CC were calculated to be 1170.30 kW at test run 1, 1474.50 kW at test run 2, 1650.12 kW at test run 3 and 1702.50 kW at test run 4. ●Exergy destruction rate increased from 33.72 kW to 60.65 kW for AC, from 37.98 kW 59.27 kW for CeC during increasing load values from 284 N.m to 579 N.m ●The exergy destruction rate values for HPT and PT showed variations during the test runs, where the minimum value was 12.38 kW for HPT and 50.49 kW for PT. Finally, the ED had maximum exergy destruction rate at the test run #4 with a value of 109.27 kW.
[15]	2017	Turboprop /JP8 ($C_{12}H_{23}$)	Advanced and conventional exergy analysis was applied to aircraft turboprop engine. ●The ambient temperature and the pressure were 298.15 K and 101.33 kPa.	●CC had the highest exergy destruction with the rate of 1807.95 kW and the lowest exergy efficiency with 66.74%. ●CC had the maximum relative exergy consumption ratio with 50.94%, the maximum fuel exergy depletion ratio with 42.47%, the maximum productivity exergy lack ratio with 250.06%, and the maximum improvement exergy potential with 601.32 kW.
[11]	2017	Turbojet/ Biodiesel or JP8	Exergy analysis was applied to a small-scale turbojet engine operating with biofuel or conventional fuel for comparing exergetic performance parameters. ●The ambient temperature and the pressure were 308 K and 91.40 kPa.	●For conventional fuel, exergy destruction rates of the AC,CC, and HPT were calculated as 10.10 kW, 111.98 kW, and 0.70 kW, respectively, for biofuel they were calculated as 10.54 kW, 114.21 kW, and 0.46 kW, respectively. ●For conventional fuel , exergy efficiency of AC, CC, HPT were calculated as 75.22% , 48.34%, 98.44% ,respectively, for biofuel these were calculated as 74.52%, 47.68% and 99.00%,repectively. ●The higher improvement potential rate was observed in CC as 59.76 kW for the biofuel operation and 57.85 kW for conventional jet fuel operation.

[22]	2017	Turbojet /kerosene	Idle, part load one, part load two and full load was selected as operating condition for exergy analysis and small scale gas turbine jet engine. ● The ambient temperature and the pressure were 289.15 K and 102 kPa.	●From idle to full load case, exergy efficiencies of TJE components increased. For example, exergy efficiency of TJE was 3.9% at full load, 2.7% at part load two, 1.2% at part load one, 0.0001% at idle. ●The maximum exergy efficiencies were observed 68% in GT for idle operation ,79% in GT for part load one operations , 80,6% in CC for part load two operation, 81% in CC for full load operations. ●The maximum exergy destructions occurred in CC as 35.1 kW, 40.3 kW, 36.6 kW and 47.9 kW, respectively for four loading.
[9]	2016	Turboshaft /JET A-1 ($C_{12}H_{23}$)	For exergy analysis, energy and exergy-based computational approach applied to a turboshaft engine. ● The ambient temperature and the pressure were 288 K and 101.3 kPa.	●While the exergetic efficiency of the turboshaft was calculated as 27.5% with 1500 kW product exergy, the greatest exergy efficiency in its component was calculated to be 91.4% at the GT . ●CC has the highest exergy destruction with 1244.01 kW. ●The lowest exergetic improvement potential was calculated as 10.02 kW at the AC.
[6]	2016	Turboshaft/ JP-8 ($C_{12}H_{23}$)	Four different load values have been selected to apply the exergy analysis to a turbojet engine. These were 284 N • m for test # 1, 436 N • m for test # 2, 547 N • m for test # 3 and 579 N • m for test # 4. ● The ambient temperature and pressure was 288 .15 K and 92 kPa	●The exergy efficiency values for the CC were clearly visible and an improvement of 10% was observed during the increase in torque from 284 N • m to 579 N • m. While no significant change was observed in the exergetic efficiencies of the AC and CeC modules, HPT, PT and ED modules had minor changes. The exergic efficiency of the turboshaft engine was calculated for all load values and the fuel exergy amounts were 2985.7 kW for test # 1, 3964 kW for test # 2, 4777.12 kW for test # 3 and 5098.65 kW for test # 4. ●Exergy destruction values for CC were obtained as 1170.30 kW in test # 1, 1474.50 kW in test # 2, 1650.12 kW in test # 3 and 1702.50 kW in test # 4. ●During the change from load value of 284 Nm to 579 Nm, the exergy destruction value for AC increased from 33.72 kW to 60.65 kW while for CeC increased from 37.98 kW to 59.27 kW. ●However, relative exergy destruction, fuel depletion ratio, productivity loss , exergetic improvement potential values results of engine components were given in [6].
[25]	2016	Turbofan/ JET A1	Six exergo- sustainability indicators were investigated for turbofan engine. ●The ambient temperature and the pressure were 288.15 K and 101.35 kPa.	●Total inlet exergy, total destructed exergy, the waste exergy, exergy efficiency, waste exergy ratio, recoverable exergy ratio, exergy destruction factor, environmental effect factor, exergetic sustainability index were observed to be 46.96 MW,25.41 MW,16.37 MW,0.11,0348,0 ,0.541,3.163,0.316, respectively.
[26]	2015	Turbojet /kerosene	Exergy analysis was applied to turbojet in different mach number (0.4, 0.6 and 0.8)	●For 0.4 mach number, the highest exergy destruction was observed in AB, then CC,EN,AC,GT,DF, respectively. The highest exergy efficiencies also were observed in DF, then GT,AC ,EN,AB,CC respectively. ●All nozzle pressure ratio, the SFC increased by increase in the Mach number of the turbojet engine. In addition, increase in the after burner temperature and Mach number have increased exergy efficiency of the after burner.
[16]	2015	Turbofan/ JET A1 $C_{12}H_{23}$	Exergetic sustainability indicators were applied to a medium-range commercial aircraft engine for constant reference environment and ground running conditions. ● The ambient temperature and the pressure were 288 K and 101.4 kPa	● CC, HPC and fan had exergy destruction rates of 58%, 17.7%, and 10.4%, respectively. CC also had highest exergetic improvement potential rates with 2 MW. ● Exergy efficiencies of fan, LPC, HPC,CC, LPT, and HPT have been observed as 86.4%, 87%, 89%, 85%, 98.6%, and 98.2% respectively for a reference environment. ●The overall exergy efficiency of TFE used first exergy-based sustainability indicator, has been calculated as 31.5%.

[23]	2015	Turbofan/ kerosene $C_{11}H_{21}$	Advanced exergy analyses were applied to TFE in this paper. ●The ambient temperature and pressure were 288.15 K and 101.352 kPa.	●The highest exergy destruction had occurred in the combustion chamber with 46.777 MW. Exergy destruction of LPAC, HPAC, GT were determined as 1,709, 2.818, 0.543, 51.847 MW. ●Exergy efficiency of LPAC,HPAC, CC,GT, overall engine were determined as 89%, 86%,60,6%,98.6%,3.13%,respectively. ●Maximum relative exergy destruction, fuel depletion ratio, productivity loss, and exergetic improvement potential of LPAC, HPAC, CC, GT were given as 0.912, 0.212,0328 18.439 for CC.
[17]	2015	Turbofan/ kerosene $C_{11}H_{21}$	An exergy analysis was applied to a turbofan UAV engine over the course of a surveillance mission flight. ● Air temperature and pressure different for flight phase points 1-10 and were given in [17].	●The exergy destruction rate of the engine were 16820.317 kW, 16564.379 kW, 2433.206 kW, 2520.04 kW, 3152.758 kW, 2275.855 kW, 1353.157 kW, 1365.83 kW, 2520.04 kW and 16998.769 kW from flight phase points 1-10, respectively. ●The highest exergy destruction rate was observed as 14492.396 kW at flight phase point 1 for CC, 445.130 kW at flight phase point 2 for AC, 146.473 kW at flight phase point 2 for HPT, 578.281 kW at flight phase point 2 for LPT, 245.508 kW at flight phase point 10 for BPC. ●Exergetic performance parameters results of engine components were given in [17] for flight phase points 1-10.
[18]	2015	Turbofan/ JET A1 $C_{12}H_{23}$	Exergy analysis was applied to turbofan engine for determining sustainability metrics and exergetic performance parameters. ●The ambient temperature and pressure were 288.15 K and 101.35 kPa.	●The exergy efficiency of the engine has been calculated as 29.6% ●Waste exergy ratio was found to be 0.20. ●Exergy destruction factor was calculated to be 0.5037. ●Recoverable exergy amount was zero due to the emissions released from exhaust cannot be recoverable in the engine. ●Environmental effect factor was found to be 0.675 ●Exergetic sustainability index was determined to be 1.48.
[27]	2014	Turbofan /JET A1 $C_{12}H_{23}$	Some exergetic measures which are fuel depletion ration, productivity lack ratio, fuel exergy factor, product exergy factor and improvement potential rates have been calculated at maximum power setting. ●The ambient temperature and pressure were 288.15 K and 101.35 kPa.	● At the take-off condition, the fuel depletion ratio values ranges from 0.2% to 12.6% in engine components. While HPT and LPT have good fuel depletion ratios which changes between 0.2-0.4, CC have maximum fuel depletion ratio with12.6% due to maximum irreversibilities. ●Productivity lack ratio was found to be CC with 15.3%, HPC with 2.45%, and fan with 2.01%, LPT with 0.53% and HPT with 0.2 at the take condition. On the other hand, greatest fuel exergy factor and product exergy factor were observed in the CC with 49.5% and 44.4%, respectively. While minimum improvement potential rate was observed in HPT with of 0.01 MW, maximum improvement potential rate was found in CC with 4.82 MW.
[19]	2014	Turboprop / JP-8	Exergy analysis was applied to turboprop engine according to the shaft power , namely Case A and the shaft power plus the kinetic exergy rates, namely Case B using the exergoeconomic, sustainability and environmental damage cost analysis methods at different power loadings. ● The ambient temperature and pressure were 298.15 K and 93.6 kPa.	● While the exergetic efficiency values of the TPE were observed as 20.5%,22.3%, 23.1% and 23.8% for 75%-mode, at 100%-mode, at MIL mode and at takeoff-mode, respectively in case A, they were found to be 23.4%, 24.9%, 25.6% and 26.3% for 75%-mode, at 100%-mode, at MIL mode and at takeoff-mode, respectively in case B. ● On the other hand,while the exergetic improvement potential rates were calculated to be 24.46 GJ/h, 29.21 GJ/h ,30.1 GJ/h and 30.32 GJ/h for 75%-mode, at 100%-mode, at MIL mode and at takeoff-mode in case A, they were found to be 22.7 GJ/h, 27.25 GJ/h, 28.11 GJ/h and 28.33 GJ/h for 75%-mode, at 100%-mode, at MIL mode and at takeoff-mode, respectively in case B. ●Exergoeconomic, sustainability, environmental damage cost analysis results were given in [19].

[20]	2013	Turboprop/ JP-8 ($C_{12}H_{23}$)	Exergy analysis was applied to turboprop engine according to both the shaft power (Case A) and the shaft power plus the kinetic energy rates of the exhaust gases (Case B) at various power loading operation modes like 75%, 100%, Military and Takeoff. ● The ambient temperature and pressure were 298.15 K and 93.6 kPa.	●As take into account the kinetic exergy of the exhaust gaseous, exergy efficiency and improvement potential of TPE increased and energy losses rate, the exergy consumption rate, the fuel depletion ratio, the productivity lack ratio and the fuel-production ratio decreased. For example, exergy efficiency of TPE was calculated to be 20.5% at 75%- mode and 23.8% at Takeoff mode for Case A and these values were found as be 23.4% at 75%-mode and 26.3% at Takeoff mode for Case B. ● In CC, relative exergy destruction ratio was maximum with approximately 56% for Case A and maximum with approximately 58% for case B.
[2]	2013	Turbojet/ JET A-1 ($C_{12}H_{23}$)	Exergy analysis was applied to a turbojet engine for two altitudes: sea level and 11,000 meters. ●The ambient temperature and pressure were 298.1 K and 101.3 kPa.	●At sea level and 200 m/s speed, the highest exergy efficiency was observed by the compressor at 96.7%, then the nozzle with 93.7% and turbine with 92.3%. However, the lowest exergy efficiencies was found for the afterburner with 54.8% and followed by the combustion chamber with 80.4%). ●When velocity was reduced from 200 m/s to 100 m/s, the exergy efficiencies the of all components decreased. ●At 11,000 m and 200 m/s speed, the compressor had the highest exergy efficiency at 95.7%, then diffuser with 94.8%, and nozzle with 90.5%. ●For per centigrade degree increase in inlet air temperature, the engine exergy efficiency was reduced 0.45% .
[29]	2013	Turboprop/ Jet A-1 ($C_{12}H_{23}$)	Exergo-sustainability analysis applied to turboprop engine for the phases of a flight. ● The ambient temperature and pressure were 281 K and 92.4 kPa	●The taxi and landing phases had minimum exergy efficiency and exergetic sustainability index, maximum waste exergy ratio, exergy destruction ratio and environmental effect factor with the value of 0.206,0.26, 79.4%, 48% and 3.85, respectively. ●In the climb, maximum cruise and continuous, normal and maximum take-off and automatic power reverse phases, exergy efficiency, waste exergy ratio and exergetic sustainability index of the turboprop were observed to be in the range of 0.274-0.290, 0.726-0.708 and 0.380-0.410, respectively. ● As shaft torque increased from 240 to 630 N m, the exergetic sustainability index increased from 24% to 29.2%, waste exergy ratio decreases from 79.40% to 70.80%, exergy destruction ratio decreased from 48% to 41%, environmental effect factor decreased from 3.85 to 2.43, and exergetic sustainability index increased from 0.26 to 0.41.
[28]	2013	Turboprop / JET A-1 ($C_{12}H_{23}$)	Exergo-environmental analysis were applied to turboprop engine at maximum power setting ●The ambient temperature and pressure were 279 K and 93 kPa.	●Component related environmental impact constituted approximately 16.85% of total environmental impact. According to these rates, the compressor and gas turbine almost had same impact rate and can be considered first to improve in case of component related environmental impact. ● According to exergetic results, the biggest candidate for improving was the combustion chamber. This component created 68.98% of the overall environmental impact while 96.8% of this impact was associated with exergy destruction.
[30]	2012	Turbojet/ Kerosene ($C_{12}H_{23}$)	Exergy analysis was applied to a turbojet engine for determining some design parameters effects. ● The ambient temperature and pressure were 229,5 K and 30,73 kPa.	● As the compressor pressure ratio increased, exergy efficiency of compressor increased. For example, the increase in compressor pressure ratio from a value 2 to 7 caused increasing of the exergy efficiency of the compressor from 82.87% to 86.83%.
[3]	2010	Turbofan /JET-A1 ($C_{12}H_{23}$)	Exergy and thermo-economic analysis were applied to turbofan engine for a typical commercial flight.	●For global model, cruise which is longest phase presented the maximum exergy efficiency with value of 26% demonstrating that the engine design point is the most efficient one. ●For local model, engine destroyed exergy was inversely proportional to thrust and between 70% and 80% of irreversibility.

[31]	2008	Turbojet /JET A 1 ($C_{12}H_{23}$)	Exergy and exergoeconomic analysis were applied to an aircraft Jet Engine. ●The ambient temperature and pressure were 289,26 K and 101.325 kPa.	●The exergetic efficiencies of AC, CC, GT, ED, whole TJE was found to be 81.33%, 55.13%, 96.05%, 88.41%, 97%, and 34.84%, respectively. The exergetic efficiency of the TJE was accounted for 34.84% with 2421.86 kW as exhaust gases product for thrust. ●Among the components, CC had highest exergy destruction with 3691.06 kW
[32]	2007	Turbofan/ Kerosene ($C_{12}H_{23}$)	Exergy analysis was applied to a turbofan engine using the sea level data. ●The ambient temperature and pressure were 306.5 K and 101.3 kPa.	●The exergy efficiency values of fan, compressor, HP turbine and LP turbine was found to be 90.79%, 95.19%, 95.15% and 95.54%, respectively. ● CC was the main irreversible unit with value of 35.76 MW among the other units and had the highest exergetic improvement potential with the value of 8.03 MW, followed by the fan with the value of 0.34 MW and the compressor with the value of 0.12 MW.
[33]	2007	Turbofan/ JET A 1 ($C_{12}H_{23}$)	Exergy analysis was performed for a turbofan kerosene-fired engine with afterburner (AB) for sea level and an altitude of 11 000 m. ●The ambient temperature and pressure were 298 K and 101.3 kPa.	●Exergy efficiency values of fan, compressor, combustion chamber, turbine was calculated to be 80.6%, 70.4%, 66.7%, 88.5%, respectively based on the product/fuel basis at the sea level. ● The exergy efficiencies were higher at the sea level compared to at 11 000 m altitude. ●AB had highest exergy destruction with value of 95.46 MW at the sea level, followed by the exhaust with value 58.93 MW and the combustion chamber with value of 34.09 MW.
[34]	2001	Turbojet/ Methane (CH4)	Exergy analysis was applied to a turbojet engine for flight altitudes ranging from sea level to 15 000 m. ●The ambient temperature and pressure were 288.15 K and 101.33 kPa.	●As altitude increased, the efficiency of engine decreased. For example, total rational efficiency was 0.1686 at the sea level compared with at 15 000 m with the value of 0.1536.

Nomenclature

AB afterburner operation mode
ABED afterburner exhaust duct
CC combustion chamber
GT gas turbine
CeC centrifugal compressor
AC axial compressor
ED exhaust diffuser
EN exhaust nozzle
HPC high pressure compressor
HPT high pressure turbine
HPTMS high pressure turbine mechanical shaft
LHV lower heating value of fuel (kJ/kg)
LPC low pressure compressor
LPAC low pressure axial compressor
LPT low pressure turbine
LPTMS low pressure turbine mechanical shaft
TJE turbojet engine
TFE turbofan engine
SFC specific fuel consumption

References

[1] Şöhret, Y., Ekici, S., Altuntaş, Ö., Hepbasli, A., & Karakoç, T. H. , Exergy as a useful tool for the performance assessment of aircraft gas turbine engines: A key review, *Progress in Aerospace Sciences,* Vol. 83,2016, pp. 57-69.

[2] Ehyaei, M. A., Anjiridezfuli, A., & Rosen, M. A., Exergetic analysis of an aircraft turbojet engine with an afterburner, *Thermal science*, Vol. 17, No. 4, 2013, pp. 1181-1194.

[3] Tona, C., Raviolo, P. A., Pellegrini, L. F., & de Oliveira Júnior, S., Exergy and thermoeconomic analysis of a turbofan engine during a typical commercial flight, *Energy*, Vol. 35, No.2, 2010, pp. 952-959.

[4] Tai, V. C., See, P. C., & Mares, C., Optimisation of energy and exergy of turbofan engines using genetic algorithms, *International Journal of Sustainable Aviation*, Vol. 1, No. 1, 2014, pp. 25-42.

[5] Boldon, L., Sabharwall, P., Rabiti, C., Bragg-Sitton, S. M., & Liu, L.,Thermodynamic exergy analysis for small modular reactor in nuclear hybrid energy system, *EPJ Nuclear Sciences & Technologies*, Vol. *2*, 2016, pp 23.

[6] Çoban, K., Çolpan, C. Ö., & Karakoç, T. H., Bir Helikopter Motorunun Enerji ve Ekserji Analizi. *Sürdürülebilir Havacılık Araştırmaları Dergisi*, Vol. 1, 2016, pp. 27-39.

[7] Turan, O., Energy and Exergy (ENEX) Analyses of a MD-80 Aircraft, *International Journal of Mechanical Engineering and Robotics Research*, Vol. 5, No. 3, 2016, pp.
[8] Topal, A., Topal, A., Turan, O., & Turan, O,On-design exergy analysis of a combustor for a turbojet engine: a parametric study, *Aircraft Engineering and Aerospace Technology*, Vol. 89, No.5, 2017, pp.719-724.
[9] Turan, Ö., & Aydın, H., Numerical calculation of energy and exergy flows of a turboshaft engine for power generation and helicopter applications, *Energy*, Vol. 115, 2016, pp. 914-923.
[10] Coban, K., Colpan, C. O., & Karakoc, T. H.,Application of thermodynamic laws on a military helicopter engine. *Energy*, Vol.*140*, 2017, pp. 1427-1436
[11] Coban, K., Şöhret, Y., Colpan, C. O., & Karakoç, T. H.,Exergetic and exergoeconomic assessment of a small-scale turbojet fuelled with biodiesel, *Energy*, Vol. 140, 2017, pp. 1358-1367
[12] Balogun, O., Mo, C., & Mazher, A. K. Exergy Analysis of Gas Turbine-Burner Engine, International Journal of Scientific & Technology Research, Vol.3,No.1,2014.
[13] Balli, O., Exergy modeling for evaluating sustainability level of a high by-pass turbofan engine used on commercial aircrafts, *Applied Thermal Engineering*, Vol. 123, 2017, pp. 138–155.
[14] Balli, O., Advanced exergy analyses to evaluate the performance of a military aircraft turbojet engine (TJE) with afterburner system: Splitting exergy destruction into unavoidable/avoidable and endogenous/exogenous. *Applied Thermal Engineering*, Vol. 111, 2017, pp. 152-169.
[15] Balli, O., Advanced exergy analyses of an aircraft turboprop engine (TPE). *Energy*, Vol. 124, 2017, pp. 599-612.
[16] Aydin, H., Turan, O., Karakoc, T. H., & Midilli, A.,Exergetic sustainability indicators as a tool in commercial aircraft: a case study for a turbofan engine, *International journal of green energy*, Vol. 12, No. 1, 2015, pp. 28-40.
[17] Şöhret, Y., Dinç, A., & Karakoç, T. H., Exergy analysis of a turbofan engine for an unmanned aerial vehicle during a surveillance mission, *Energy*, Vol. 93, 2015, pp. 716-729.
[18] Turan, O.,An exergy way to quantify sustainability metrics for a high bypass turbofan engine, *Energy*, Vol. 86, 2015, pp. 722-736.
[19] Balli, O., & Hepbasli, A., Exergoeconomic, sustainability and environmental damage cost analyses of T56 turboprop engine, *Energy*, Vol. 64, 2014 , pp. 582-600.
[20] Balli, O., & Hepbasli, A.,Energetic and exergetic analyses of T56 turboprop engine, *Energy conversion and management*, Vol. *73*, 2013, pp. 106-120.
[21] Berg, F. T., Principles for Aircraft Energy Mapping, Doctoral dissertation, University of Bath, Departments of Mechanical and Electrical Engineering,2013.
[22] Yucer, C. T. ,Thermodynamic analysis of the part load performance for a small scale gas turbine jet engine by using exergy analysis method. *Energy*, Vol. 111, 2016, pp. 251-259.
[23] Şöhret, Y., Açıkkalp, E., Hepbasli, A., & Karakoc, T. H. ,Advanced exergy analysis of an aircraft gas turbine engine: Splitting exergy destructions into parts, *Energy*, Vol. *90*, 2015, pp. 1219-1228.
[24] Yücer, C. T., Exergetic sustainability assessment of a gas turbine jet engine at part loads, *Anadolu Üniversitesi Bilim Ve Teknoloji Dergisi A-Uygulamalı Bilimler ve Mühendislik*, Vol.18, No.5, 2017, pp. 1018-1030.
[25] Turan, O., & Aydin, H. , Exergy-based sustainability analysis of a low-bypass turbofan engine: A case study for JT8D. *Energy Procedia*, Vol. 95, 2016, pp. 499-506.
[26] Bastani,M.,Jafari,R.,Ghasemi, H., Exergy analysis of an aircraft turbojet engine, *IJESRT*, Vol.4,No.4,2015,
[27] Turan, O., Aydın, H., Karakoc, T. H., & Midilli, A. ,Some exergetic measures of a JT8D turbofan engine ,*Journal of Automation and Control Engineering, Vol, 2, No.*2.,2014,
[28] Atılgan, R., Turan, Ö., Altuntaş, Ö., Aydın, H., & Synylo, K. ,Environmental impact assessment of a turboprop engine with

the aid of exergy. *Energy*, Vol. 58, 2013, pp. 664-671.

[29] Aydın, H., Turan, Ö., Karakoç, T. H., & Midilli, A., Exergo-sustainability indicators of a turboprop aircraft for the phases of a flight. *Energy*, Vol. *58*, 2013, pp. 550-560.

[30] Turan, O., Exergetic effects of some design parameters on the small turbojet engine for unmanned air vehicle applications. *Energy*, Vol.46, No.1, 2012, pp. 51-61.

[31] Balli, O., Aras, H., Aras, N., & Hepbasli, A., Exergetic and exergoeconomic analysis of an Aircraft Jet Engine (AJE), *International Journal of Exergy*, Vol. 5 No.5-6, 2008, pp. 567-581.

[32] Turgut, E. T., Karakoc, T. H., & Hepbasli, A.,Exergy analysis of a turbofan engine: Cf6-80, In *3rd International Green Energy Conference*, 2007.

[33] Turgut, E. T., Karakoc, T. H., & Hepbasli, A.,Exergetic analysis of an aircraft turbofan engine, *International Journal of Energy Research*, Vol. *31*, *No.*14,2007,pp. 1383-1397.

[34] Etele, J., & Rosen, M. A. ,Sensitivity of exergy efficiencies of aerospace engines to reference environment selection, *Exergy, An International Journal*, Vol. *1*, No.2, 2001, pp. 91-99.

[35] Baltacıoğlu M.K, Arat H.T., Kenanoğlu R., Exergy and performance analysis of a CI engine fuelled with HCNG gaseous fuel enriched biodiesel, *International Journal of Exergy*, 24,1,2017,39-55