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EXERGETIC, EXERGOECONOMIC AND SUSTAINABILITY ASSESSMENTS OF PISTON-PROP AIRCRAFT ENGINES

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Abstract: In this study, the exergetic, exergoeconomic, and sustainability aspects of piston-prop aircraft engines are comprehensively reviewed. These analysis and assessment tools are applied to a four-cylinder, spark ignition, naturally aspirated and air-cooled piston-prop aircraft engine in the landing and takeoff (LTO) phases of flight operations. LTO consists of four parts: takeoff, climb out, approach, and taxi. The results of energy analysis indicate that takeoff is a phase requiring high power with a maximum work rate of 111.90 kW. Maximum fuel energy and exergy rates are calculated to be 444.30 kW and 476.51 kW, respectively. The minimum total loss is found in the taxi phase, while maximum energy and exergy efficiency values are 26.76% and 24.95% in the climb out phase, respectively. Based on the results of the cost analysis, the taxi has the maximum exergy destruction cost rate with 23.41 $/h at a fixed production and 2.96 $/h at a fixed fuel. Maximum sustainability index (SI) is found to be 1.332 at the climb out phase.
Keywords: Piston-prop aircraft engine, Exergoeconomy, Exergy, SI, EXCEM.

PİSTON-PROP UÇAK MOTORLARININ EKSERJETİK, EKSERJOEKONOMİK VE SÜRDÜRÜLEBİLİR DEĞERLENDİRİLMESİ

Özet: Bu çalışmada, piston-prop uçak motorlarının ekserji, ekserjoekonomi ve sürdürülebilirlik yönleri kapsamlı bir şekilde gözden geçirilmiştir. Bu analiz ve değerlendirme araçları, 4-zamanlı, hava soğutmalı, 4-silindirli ve doğal emişli bir piston-prop uçak motoruna, uçuş operasyonunun bir bölümü olan iniş–kalkış (LTO) safhasında uygulanmıştır. LTO safhası; kalkış, tırmanma, yaklaşma ve taksi olmak üzere dört fazdan oluşur. Enerji analizi sonuçları, 111.90 kW ile en yüksek iş akımına ihtiyaç duyulan fazın kalkış olduğunu göstermiştir. Aynı fazda, yakıt enerji ve ekserji akımlarının da, sırasıyla 444.30 kW ve 476.51 kW değerleriyle, en yüksek olduğu görülmüştür. En düşük enerji ve ekserji kayıpları taksi fazında bulunurken, en yüksek enerji ve ekserji verimleri sırasıyla %26.76 ve %24.95 olarak tırmanma fazında bulunmuştur. Maliyet analizleri sonucunda, taksi fazının en yüksek ekserji yıkım maliyetine sahip olduğu görülmüştür. Bu değerler, sabit ürün yaklaşımıyla 23.41 $/h olarak hesaplanırken, sabit yakıt yaklaşımıyla 2.96 $/h olarak hesaplanmıştır. En yüksek sürdürülebilirlik indeksi (SI) ise 1.332 ile tırmanma fazında bulunmuştur.
Anahtar Kelimeler: Piston-prop uçak motoru, Ekserjoekonomi, Ekserji, SI, EXCEM.

NOMENCLATURE

$\dot{C}$	cost rate [$/h]
c	carbon mole fraction
$\dot{E}$	energy rate [kW]
$\dot{E}x$	exergy rate [kW]
f	exergoeconomic factor
g	gravity [m/s^2]
H	total enthalpy [kJ]
h	specific enthalpy [kJ/kg], hydrogen mole fraction
i	interest ratio
$\dot{m}$	mass flow rate [kg/s]
n	life time
o	oxygen mole fraction
$\dot{Q}$	heat rate [kW]
Q	heat amount [kJ]
r	relative cost difference
$\overline{R}$	ideal gas constant
s	specific entropy [kJ/kg.K]
T	temperature [K or °C]
x	mole fraction
V	velocity [m/s]
W	work [kJ]

$\dot{W}$	power or work rate [kW]
y	mole fraction of exhaust gas
$\dot{Z}$	levelized capital and OM cost

Greek letters

η	energy efficiency
ψ	exergy efficiency
ε	specific exergy [kJ/kg]
α	sulphur mole fraction
φ	chemical exergy factor

Subscripts

0	reference or dead state
cat	cooling air temperature
chem	chemical
CV	control volume
dest	destruction
ef	effective
in	input (inlet)
loss	loss
out	output (outlet)
P	product
ph	physical
u	lower

Superscripts

CI	capital investment
OM	operation and maintenance

INTRODUCTION

The internal combustion engine is the first alternative energy source to meet the highest power density and power-to-weight ratio and least volume that aircraft design has always demanded (Hiereth and Prenninger, 2007). Piston-prop aircraft, this type of design, is a combination of internal combustion engine and propeller. It is used for reducing the maximum amount of thrust (Crane, 2005). Piston-prop aircraft are designed to operate at a constant speed for long periods and over a wide range of altitudes (Jenkinson and Marchman, 2003). For aircraft operation at various altitudes and over a long range, the carburetor system design allows air to flow vertically or horizontally. This affects the inlet pressure and air-to-fuel ratio (AF) at any time. Many turbocharged aircraft engines increase flight altitude performance, while minimizing this problem (Hiereth and Prenninger, 2007; Pulkrabek, 1997).

Beside design applications, some improvements can be applied for enhancement of piston-prop aircraft efficiency. In this respect, not only energy analysis (the first law of thermodynamics), but also exergy analysis (the second law of thermodynamics), can apply. Exergy characterizes the thermodynamic quality of a given quantity of energy (Wall, 1988). In exergetic studies, (i) exergetic efficiency compares the actual than hold back the performance, and (ii) exergoeconomic, a combination of exergy analysis and economic principles, provides exact information to the system designer or operator about the systems. This information is very valuable for improving the design of energy-conversion plants.

Many researchers have performed exergy analyses of spark ignition internal combustion engines, generally used in piston-prop aircraft. Rakopoulos (1993) indicated that the exergy analysis is much more realistic than energy analysis, as it reveals the amount of available work losses. Exergy analysis points out different ways to improve the efficiency of a cycle, reduction of availability losses in combustion processes, and exhaust processes. Zhencheng et al. (1991) showed that the exergy analysis indicates the amount of work that can be recovered from the total energy loss for the spark ignition internal combustion engines. While crank angle degrees, spark plug position and compression ratio affect engine efficiency, combustion duration does not. In addition, Sezer and Bilgin (2008a; b) indicated that increasing compression ratio causes much more, but increasing equivalence ratio causes less first and second law efficiencies. Kopac and Kokturk (2005) pointed out that the best engine speed according to the energy analysis is 2040 rotations per minute (RPM) while it is 2580 RPM according to the exergy analysis. Abu-Nada et al. (2007) proved that the engine's performance, like engine speed, rises when using a gas mixture instead of air. These findings provided valuable guidelines for performance evaluation and development research into spark ignition engines. Sezer et al. (2009) reported that oxygen-saturated fuels such as methanol and ethanol are suitable in terms of exergy, less entropy production and less heat loss.

Exergy analysis indicates the theoretical limit in the development of aircraft systems (Bejan and Siems, 2001). The exergy-based approach, involving isolated and integrated aircraft system analysis, has been used for several years in the aerospace industry. Exergy-based methods applied to the aircraft in different ways. Some researchers applied to the design of aircraft integrated systems, components and to land-based power plant design (Pellegrini et al., 2007; Moorhouse, 2003; Munoz and Spakovsky, 2003). Some others applied to the design of an environmental control system (Figliola and Tipton, 2000; Figliola et al., 2003). Periannan et al. (2008) applied exergy analysis to the design and operation of aircraft system with three subsystems: propulsion, environmental, and airframe-aerodynamics.

Etelen and Rosen (2001) examined a turbojet engine aircraft for exergy and rational efficiency from sea level to 15,000 m altitude. Rational efficiency decreased from 16.9% at sea level to 15.3% at 15,000 m. In addition, a large exergy loss was demonstrated in exhaust emissions. Rosen and Etelen (2004) identified the importance of research to improve the thermodynamic efficiency of a turbojet engine rated at a typical flight cycle and to reduce losses by using exergy methods for aerospace applications. Roth et al. (2002) prepared charts showing how work potential varies with temperature, pressure, and fuel-air ratio. Leo and Perez-Grande (2004) indicated that the operating costs for aircraft system are much higher than they are for the other thermal systems, so they are high exergoeconomic factors. Other researchers have applied exergy and exergoeconomic analysis, using the SPECO (Specific-Cost Exergy Costing) method to the turbofan engines (Turgut et al., 2007; 2009a; b; Roth and Mavris, 2001).

Roth and Mavris (2001) reported the following about turbofan engines:

- Cycle pressure ratio causes exhaust outlet temperature loss;
- Turbine inlet temperature causes unbalanced combustion loss is not balanced;
- Fan pressure ratio causes exhaust residual kinetic energy losses.

To the best of our knowledge, no studies about exergetic, exergoeconomic, exergy, cost, energy and mass (the so-called EXCEM) analyses and sustainability assessment of piston-prop aircraft engines have appeared in the open literature. This was the prime motivation for conducting this study, which differs from previous conducted ones as follows: *(i)* exergy and exergoeconomic analyses are applied to piston-prop aircraft engines, *(ii)* EXCEM analysis based on fuel cost and cost investments is carried out, and *(iii)* sustainability assessment based on sustainability index (SI) is made.

DESCRIPTION OF PISTON-PROP AIRCRAFT ENGINES

The selection of the propulsion system is usually obvious from the design requirements. Aircraft speed regimes are defined, approximately, as subsonic (Mach numbers below 0.75), transonic (Mach numbers from 0.75 to 1.20), supersonic (Mach numbers from 1.20 to 5.00) and hypersonic (Mach numbers above 5.00). Mach number is the velocity of aircraft at flight altitude, divided by the speed of sound. Because piston-prop aircraft speeds are very low in comparison to the speed of sound, they are assumed to be subsonic aircraft (Raymer, 2006).

The piston-prop is a basic combination of reciprocating engine and propeller (Fig. 1). The reciprocating engine and a propeller on an aircraft reduce the maximum amount of thrust (Crane, 2005). The piston-prop was the first type of aircraft propulsion. Piston-prop aircraft constitute about three-quarters of the aircraft in the world. This is because the first private pilot license can only use a single engine piston-prop aircraft, looking at the specific area of use, training, ambulance, medicines. The most important advantages of piston-prop engines are their cost and very low fuel consumption. However, they are heavy and the occurrence of noise and vibration during operation can be counter-productive (Crane, 2005).

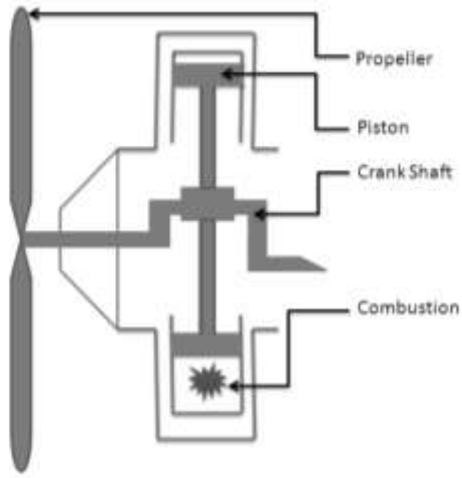

Figure 1. Piston-prop system.

Piston-prop aircraft engines can be classified according to cylinder arrangement (in-line, V-type, X-type, opposed and radial), cylinder numbering, firing order, cooling systems (air or coolant), lubrication systems (wet sump and dry-sump) and air systems (naturally aspirated and supercharged) (Crane, 2005; Kroes and Wild, 1995). Widely used piston-prop engines have the opposite sequence, spark ignition, naturally aspirated and air-cooled ones type. The use of other types of engines is less widespread.

A BRIEF HISTORY OF PISTON-PROP AIRCRAFT ENGINES

Wilbur and Orville Wright made the first aircraft flight in 1903. At that time, the internal combustion engine was only 50 years old, and the spark ignition petrol engine gasoline was only 20. The comprehensive development and use of aircraft during the World War I contributed greatly to the improvement of engines. The rotary-type radial, in-line and V-type engines were introduced at this time. After World War I, many new engines were designed. Many aircraft were sold to public, most of them were used in the early days of outdoor shows and visits to exhibit passenger flights. The radial engine was the most popular in United States during World War II (Crane, 2005; Kroes and Wild, 1995; Gunston, 1999).

The cost of private jet ownership soared due to the proliferation of product liability claims, so commercial manufacturers virtually stopped producing reciprocating engine aircraft in the 1980s. In the mid-1990s, civil liability law reform encouraged some manufacturers to re-enter the field of private aircraft (Crane, 2005).

Extensive development and use of aircraft during and after World War I resulted in a great improvement in engines. Examples are given below (El-sayed, 2008):

- Rotary-type engines (Gnome-Monosoupape and the Bentley)
- In-line engines (Hispano-Suiza)
- Inverted in-line engines (Menasco Pirate, model C-4)
- V-type engines (Rolls-Royce V-12, U.S.-made Liberty V-12)
- Radial engines (28 cylinder Pratt & Whitney R-4360 engine was used extensively at the end of World War II and then for both bombers and civil transports)
- Opposed, flat, or O-type engines.

MODELLING

There are two categories of aircraft operations: ground-based and flight-based. Ground-based operations include fuel and passenger service, baggage handling, and maintenance activities; flight-based operations cover landing and takeoff (LTO) phase and cruise phase (ICAO, 2007).

Exergy, exergoeconomic, EXCEM analyses, and sustainability assessment methods are used in the performance evaluation of piston-prop aircraft engine. In this regard, the piston-prop aircraft engine may be modeled using the following relations.

General Energy Equations

A simple system for energy flow of the control volume is given in Fig. 2.

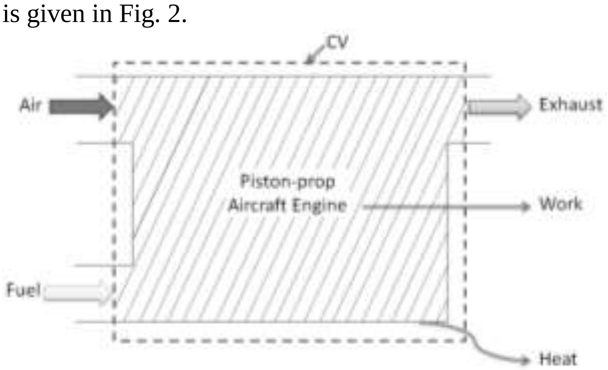

Figure 2. Energy flow of piston-prop aircraft engine.

During steady-state, a process of an open thermodynamic system, the total rate of mass entering the control volume is usually equal to the total rate of mass leaving. Therefore, the total amount of mass contained within a control volume does not change with time (m_{CV} = constant).

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

Same as the mass balance, the total energy content of a control volume remains constant (E_{CV} = constant) during a steady-state process, so the rate form of the general energy balance for a steady-state open thermodynamic system reduces to (Cengel and Boles, 2006):

$$\dot{E}_{in} = \dot{E}_{out} \tag{2}$$

$$\dot{Q}_{in} + \dot{W}_{in} + \sum_{in} \dot{m}\left(h + \frac{V^2}{2} + gz\right) = \dot{Q}_{out} + \dot{W}_{out} + \sum_{out} \dot{m}\left(h + \frac{V^2}{2} + gz\right) \tag{3}$$

where the subscripts *in* and *out* represent inlet and output states, respectively. While $\dot{Q}$ denotes the heat rate, $\dot{W}$ the work rate, $\dot{m}$ the mass flow rate, h the specific enthalpy, V the velocity, g the gravitational acceleration and z the elevation of the center of gravity of a system relative to some arbitrarily selected reference level.

Here, the best way to measure engine work in internal combustion engines is to use the area under the *P-v* diagram of the process. All processes of a cycle must be known to find the work. There are several hypotheses to determine an ideal cycle (Heywood, 1988). Another method of finding work value for the design altitude or motor performance rates is to use the engine's user manual.

Energy input rate to a control volume is found using lower heating value, H_u and mass flow rate of fuel, $\dot{m}_{fuel}$ as follows:

$$\dot{E}_{fuel} = \dot{m}_{fuel} H_u \tag{4}$$

Heat loss rate of the control volume is evaluated as the difference between the energy input rate and the net work rate by,

$$\dot{Q}_{loss} = \dot{E}_{fuel} - \dot{W} \tag{5}$$

Thermal efficiency of the control volume is defined as the ratio of the net work rate to the fuel energy input rate as follows:

$$\eta = \frac{\dot{W}}{\dot{E}_{fuel}} \tag{6}$$

General Exergy Equations

Exergy is defined as the maximum possible work as a system undergoes a reversible process from a specified initial state to the state of its environment, that is, dead state. It is therefore a property of the system-environment combination and not of the system alone (Cengel and Boles, 2006).

Exergy balance of a steady-flow process is written as follows (Cengel and Boles, 2006):

$$\dot{E}x_{in} = \dot{E}x_{out} \tag{7}$$

$$\dot{E}x_{in} = \dot{E}x_{exh} + \dot{E}x_{W} + \dot{E}x_{loss} + \dot{E}x_{dest} \tag{8}$$

$$\sum \dot{m}_{in}\varepsilon_{in} = \sum \dot{m}_{out}\varepsilon_{out} + \dot{W} + \sum\left(1 - \frac{T_0}{T_{cat}}\right)\dot{Q} + \dot{E}x_{dest} \tag{9}$$

where ε is specific flow exergy and $\dot{E}x_{dest}$ is exergy destruction (irreversibility) rate, T_0 is reference (dead) state temperature to be 298 K and T_{cat} is cooling air temperature to be nearly 393 K, while $\dot{Q}$ is output heat rate from the aircraft engine to the environment through the cooling air of the engine, which is given by (Caliskan et al., 2009);

$$\dot{Q} = \dot{m}_{fuel}H_u - \left(\dot{W} + \dot{m}_{out}\Delta h_{out}\right) \tag{10}$$

where $\Delta h = h - h_0$, while h is enthalpies of the exhaust gases at measured exhaust temperature and h_0 is enthalpies of the exhaust gases at reference (dead) state temperature. In there, mout is the total mass of exhaust gas species and Δh_{out} is calculated from the sum of enthalpy differences $(h - h_0)$ of all exhaust gas species (Caliskan et al., 2009).

Input exergy rate (fuel exergy rate, $\dot{E}x_{fuel}$) includes only the chemical exergy. Exergy input rate can be described by

$$\dot{E}x_{in} = \dot{m}_{fuel}\varepsilon_{fuel} \tag{11}$$

where ε_{fuel} is the specific exergy of the fuel, which can be defined as:

$$\varepsilon_{fuel} = H_u\varphi \tag{12}$$

where φ is the chemical exergy factor. Chemical exergy factor is explained as follows (Kotas, 1995):

$$\varphi = 1.0401 + 0.1728\frac{h}{c} + 0.0432\frac{o}{c} + 0.2169\frac{\alpha}{c}\left(1 - 2.0628\frac{h}{c}\right) \tag{13}$$

where h/c, o/c and α/c are the mole fractions of hydrogen/carbon, oxygen/carbon and sulphur/carbon for liquid fuels.

Output exergy (exhaust exergy) contains thermomechanical and chemical exergies. Specific thermomechanical and specific chemical exergy are separately calculated for each exhaust production (Caliskan et al., 2009). Specific thermomechanical exergy can be defined as,

$$\varepsilon_{tm} = \left(h - h_0\right) - T_0\left(s - s_0\right) \tag{14}$$

where s is the specific entropy, h is the specific enthalpy and the subscript “0” denotes the dead (reference) state. Values of h and s can be easily found from Ref. (Cengel and Boles, 2006) using exhaust temperature of the fuel. Chemical exergy of the exhaust gases is found using Eq. (15). Mole fraction of the exhaust gases is calculated by balancing real combustion equations of the fuels with emission measurement (Caliskan et al., 2009).

$$\varepsilon_{chem} = \overline{R}T_0 In\frac{y}{y^e} \tag{15}$$

where $\overline{R}$ is the general gas constant, T_0 is the environment temperature, y is the mole fraction of exhaust gas component and y^e is the mol fraction of the component in the environment defined in Table 1 (Moran and Shapiro, 2000).

Table 1. Reference environmental (Moran and Shapiro, 2000).

Reference Component	***Mole Fraction (%)***
N_2	75.6700
O_2	20.3500
CO_2	0.03450
H_2O	3.03000
CO	0.00070
SO_2	0.00020
H_2	0.00005
Others	0.91455

Exhaust exergy rate ($\dot{E}x_{exh}$) can be explained as follows:

$$\dot{E}x_{exh} = \sum m_i\left(\varepsilon_{tm} + \varepsilon_{chem}\right)_i \tag{16}$$

where m_i is the mass rate of the combustion products, ε_{tm} and ε_{chem} are the specific thermomechanical exergy and chemical exergies of exhaust gases, respectively.

Exergetic efficiency provides a true measure of the performance of an energy system from the thermodynamic viewpoint (Bejan et al., 1996). Exergetic efficiency can be found as follows (Dincer and Rosen, 2007):

$$\psi = \frac{\dot{W}}{\dot{E}x_{in}} \tag{17}$$

General Exergoeconomic Equations

One of the most important things in a thermal system, for determining maintenance and operation values, is cost. This cost is paid to obtain a service or a product and will be reviewed in two parts: fixed and variable. Fixed costs have a serious effect on the production quantity. They are listed as initial investment of system, taxes, insurances and depreciation. Maintenance costs also are sometimes listed in this category. Variable costs, which do not have direct effect on production volumes, can include fuel, worker salary, sources, raw, energy and escalation. The first step of an economic analysis is to determine the total initial investment costs of a system (Turgut et al. 2009a).

Because there is a need to collect different arrangements (expenditures) under the same type, some equations, used in exergoeconomic analysis, must be known. Before starting the exergoeconomic analysis, its related equations should be written, as represented in Table 2 (Bejan et al., 1996).

In an economic analysis of a thermal system, annual values of carrying charges, fuel costs and operating and maintenance expenses supplied to the overall system are necessary inputs.

The exergoeconomic model of a system consists of cost balance and auxiliary costing equations. Cost balance of whole system is [40];

$$\dot{C}_p = \dot{Z} + \dot{C}_{fuel} \quad (25)$$

$$c_p \dot{E}x_p = \dot{Z} + c_{fuel} \dot{E}x_{fuel} \quad (26)$$

where $\dot{C}_p$ and $\dot{C}_{fuel}$ are the cost rates associated with the product and the fuel, c_p and c_{fuel} are the average unit cost of the product and the fuel, $\dot{E}x_P$ and $\dot{E}x_F$ are exergy rate of the product and the fuel and $\dot{Z}$ denotes overall capital investment ($\dot{Z}^{CI}$) and operating and maintenance ($\dot{Z}^{OM}$) cost rates (Bejan et al., 1996).

$$\dot{Z} = \dot{Z}^{CI} + \dot{Z}^{OM} \quad (27)$$

Evaluating the cost effectiveness of the system in an iterative conventional exergoeconomic optimization, the cost rate associated with the exergy destruction within the component is considered (Tsatsaronis, 2008);

$$\dot{C}_{dest} = c_{fuel} \dot{E}x_{dest} \quad (28)$$

In this equation, product is fixed. If fuel rate is fixed, $\dot{C}_{dest}$ could be obtained by:

$$\dot{C}_{dest} = c_p \dot{E}x_{dest} \quad (29)$$

The relative cost difference r_k is defined by (Bejan et al., 1996):

$$r_k = \frac{c_p - c_{fuel}}{c_{fuel}} \quad (30)$$

In evaluating the performance of components, the relative significance of each category should be known. Exergoeconomic factor is defined as a ratio of the contribution of the non-exergy-related cost to the total cost increase and given by (Bejan et al., 1996):

$$f = \frac{\dot{Z}}{\dot{Z} + c_{fuel} \dot{E}x_{dest}} \quad (31)$$

EXCEM Analysis

The aim of the EXCEM analysis is to establish a basis for an incorporated methodology for exergy, energy, economic and environmental decisions. EXCEM analysis provides a wide vision on a system scheme for energy, exergy, economic and mass flow rates (Rosen and Dincer, 2003).

A general balance for a quantity in a system may be written as (Orhan et al., 2010);

Input + Generation – Output – Consumption
= Accumulation (32)

where input and output refer to quantities entering and exiting through system boundaries. This relation is applied for mass, energy, exergy and economic values.

Table 2. Some cost relations adapted from Ref. (Bejan et al., 1996).

Symbol	*Term*	*Equations*	*No*
i_{ef}	Effective rate of return	$i_{ef} = (1 + (r/m))^m - 1$	(18)
P	(P/F,i,n), Single-payment present-worth factor or single-payment discount factor	$P = F\left(1/(1+i_{ef})^n\right)$	(19)
	(P/A,i,n), Uniform-series present-worth factor	$P = A\left\{\left((1+i_{ef})^n - 1\right)/i_{ef}(1+i_{ef})^n\right\}$	(20)
F	(F/P,i,n), Single-payment compound-amount factor	$F = P(1+i_{ef})^n$	(21)
	(F/A,i,n), Uniform-series compound-amount factor	$F = A\left\{\left((1+i_{ef})^n - 1\right)/i_{ef}\right\}$	(22)
CRF	Capital-cost factor	$CRF = i_{ef}(1+i_{ef})^n / \left((1+i_{ef})^n - 1\right)$	(23)
CELF	Constant-escalation levelization factor	$CELF = \frac{k(1-k^n)}{1-k} CRF$	(24)

To find the results, we use the EXCEM relations and approaches, explained in Refs. (Rosen and Dincer, 2003; Orhan et al., 2010).

Mass and energy cannot be generated or consumed. Consequently, the general balance for system becomes (Orhan et al., 2010):

Mass input – Mass output = Mass accumulation (33)

Energy input – Energy output = Energy accumulation (34)

While exergy, not the same energy, can be consumed, cost can be generated. Consequently, the general balance for system becomes (Orhan et al., 2010):

Exergy input – Exergy output – Exergy consumption = Exergy accumulation (35)

Cost input + Cost generation – Cost output = Cost accumulation (36)

Sustainability Assessment

The sustainability index (SI) method allows for the efficient use of resources. The SI method is directly related to exergy efficiency (Ψ), as given below (Rosen et al., 2008):

$$SI = \frac{1}{1-\psi} \tag{37}$$

AN ILLUSTRATIVE EXAMPLE

In this study, energy, exergy, exergoeconomic, and EXCEM analyses, and sustainability assessment methods are applied to a naturally aspirated piston-prop aircraft engine with a gasoline-fired 5.24 L four-stroke, four-cylinder type. Some fuel and engine specifications are shown in Table 3.

Exhaust emission values of engine in all phase of LTO were taken from Ref. (FACO, 2010), as shown in Table 4.

Table 3. Piston-prop aircraft engine specifications.

	Properties	*Values*
Engine†	Compression ratio	7.5:1
	Maximum power	119 kW at 2700 RPM
Fuel	Typical formula	C_8H_{18} (isooctane)
	Lower heating value	44,430 kJ/kg*

† Engine parameter adapted from Aircraft Owner Operation Handbook.
* These values were obtained from Ref. (Cengel and Boles, 2006).

Table 4. Emission values during LTO phases (FACO, 2010).

Operation phases	*Duration (min.)*	*Fuel consumption (kg)*	*CO (g)*
Takeoff	0.3	0.18	146.88
Climb out	2.5	1.20	1004.40
Approach	3	0.86	601.34
Taxi	12	0.93	645.01

Energy Analysis

LTO is the largest part of the operation. Moreover, LTO properties are equal to sea-level properties. In this study, P_0 and T_0 are assumed to be 101.32 kPa and 298 K, respectively. The energy analysis of the test engine was performed first. The results are shown in Table 5.

Table 5. Results of energy analysis.

Operation phases	Takeoff	Climb out	Approach	Taxi
Performance rates, (%)	100	85	45	12
$\dot{m}_{fuel}$, **(kg/s)**	0.01	0.008	0.0048	0.0013
$\dot{W}$, **(kW)**	111.90	95.12	50.36	13.43
$\dot{E}_{fuel}$, **(kW)**	444.30	355.44	213.26	57.76
$\dot{Q}_{loss}$, **(kW)**	332.40	260.32	162.91	44.33
η, **(%)**	25.19	26.76	23.61	23.25

Exergy Analysis

All the net exergy rates were calculated using Eqs. (9) – (11), and (16). The net exergy work rate is equal to net work rate. The results of net exergy work rates, fuel exergy rates, exergy loss rates, exergy destruction rates and exergy efficiency at four different phases of LTO are presented in Table 6.

Climb out phase has the most exergetic efficiency with 24.95% (196.65 kW), while take off and approach phases have the second and third ones with the values of 23.47% (248.55 kW) and 22.02% (118.58 kW). Taxi phase has the lowest exergetic efficiency with 21.68% (33.77 kW).

Table 6. Results of exergy analysis.

Operation phases	Takeoff	Climb out	Approach	Taxi
$\dot{Ex}_W$, **(kW)**	111,85	95,12	50,36	13,43
$\dot{Ex}_{dest}$, **(kW)**	248,55	196,65	118,58	33,77
$\dot{Ex}_{exh}$, **(kW)**	68,02	54,79	37,84	8,89
$\dot{Ex}_{loss}$, **(kW)**	48,09	34,65	21,95	5,86
$\dot{Ex}_{in}$, **(kW)**	476,51	381,21	228,73	61,95
ψ, **(%)**	23,47	24,95	22,02	21,68

Exergoeconomic Analysis

Some assumptions made for exergoeconomic analysis in this study are:

- Service life of the piston-prop aircraft is 15 years (This duration is equal to airframe overhaul maintenance).
- The interest rate is 10%.
- The average number of flight hours per year is 550.

- AVGAS fuel cost is 3.07 $/L (in Turkey).
- A four-cylinder, spark ignition, naturally aspirated and air-cooled piston-prop aircraft engine cost is taken on average $39,000 (Lycoming, 2010).
- An increase of 6% in the fuel prices over a period of 15 years is taken.
- Six 50-hour maintenance, five 100-hour maintenance and one annual maintenance are applied in one year.

The annual fuel consumption cost of a piston-prop aircraft engine is calculated as 42,772.38 $/y and 96,704.24 $/y for the first and last years, respectively. After an additional levelizing process, the levelized fuel costs are obtained to be 63,507.84 $/y.

The maintenance cost for a whole aircraft is found to be 3,409 $/y. The ratio of the engine maintenance within the maintenance cost is almost 8% (Turgut et al., 2009a; Willcox, 2004). Hence, the levelized engine maintenance costs are obtained to be 404.93 $/y.

The exergy destruction cost rates for the entire engine for all phases of LTO are presented in Fig. 3. The interesting point in these two figures is that the exergy destruction cost ratios of the units are roughly the same, while the exergy destruction cost rates are different. Exergy destruction cost rate calculation methods, fixed fuel and fixed production, define the minimum and maximum limits (Bejan et al., 1996).

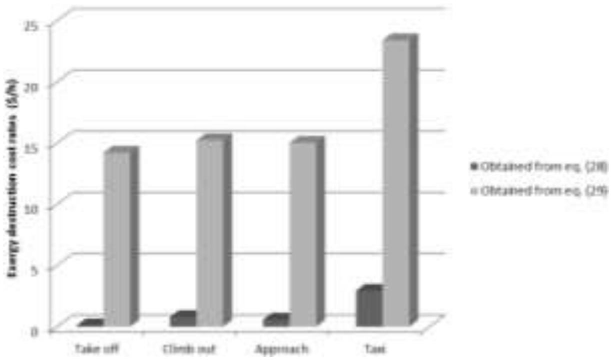

Figure 3. Exergy destruction cost rates for fuel production methods.

Exergy destruction rate of taxi with fixed production is quite a lot based on takeoff, climb out and approach (Fig. 3). Duration of the taxi phases, so the high fuel consumption, is the simple explanation of this result for the piston-prop aircraft. Besides, this is not seen with fixed fuel exergy destruction rate values.

The relative cost ratio parameter is shown in Fig. 4. In this figure, the takeoff phase of LTO has the most relative cost difference with 116.06%. It is followed by the approach and climb out phases with 24.89% and 18.00% respectively. Taxi phase of LTO has the least relative cost difference with 6.94%.

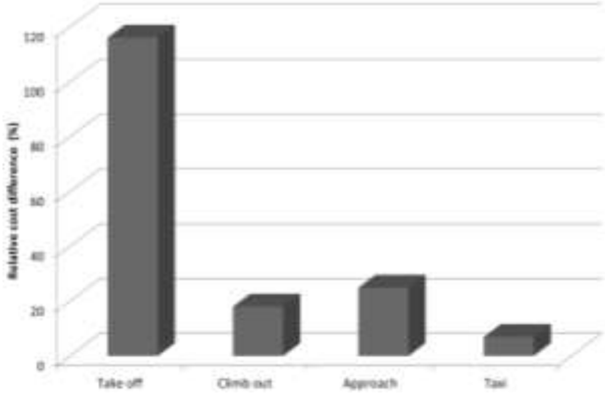

Figure 4. Relative cost difference.

Exergoeconomic factor ratios are shown in Fig. 5. Takeoff has the highest ratio with 98.81%, while taxi has the lowest ratio with 77.34%. Approach and climb out have the second and third ones with the values of 94.54% and 92.62%, respectively.

EXCEM Analysis

System analysis was conducted for each phase individually. The results of EXCEM analysis are shown in Fig. 6.

Takeoff, the most work demanding phase, required the most energy and exergy input, because a huge weight must lift in a short time. To achieve this, more power is needed. Despite energy and exergy values, the cost of taxi phase is twice that of the takeoff, climb out and approach phases combined. Hence, there is no difference in the cost of the produced work. As the system cost, 10,063 $/h, is fixed.

Sustainability Assessment

A sustainability impact shows the affects of waste emissions. At this point, desired condition is the minimum impact on the environment. So, SI helps to indicate this situation. Sustainability indexes of this system based on takeoff, climb out, approach, and taxi phases are 1.307, 1.332, 1.282, and 1.277, respectively, while SI and exergy efficiency vs LTO phases are illustrated in Fig. 7.

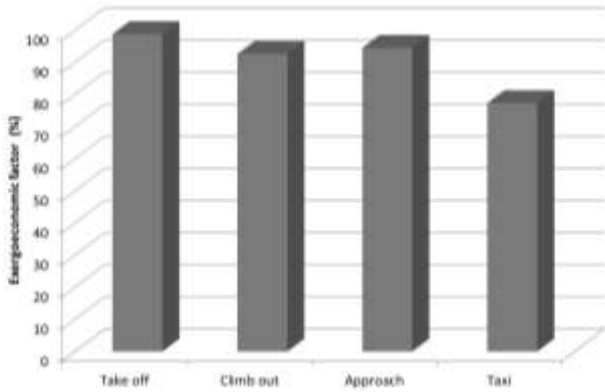

Figure 5. Exergoeconomic factor values.

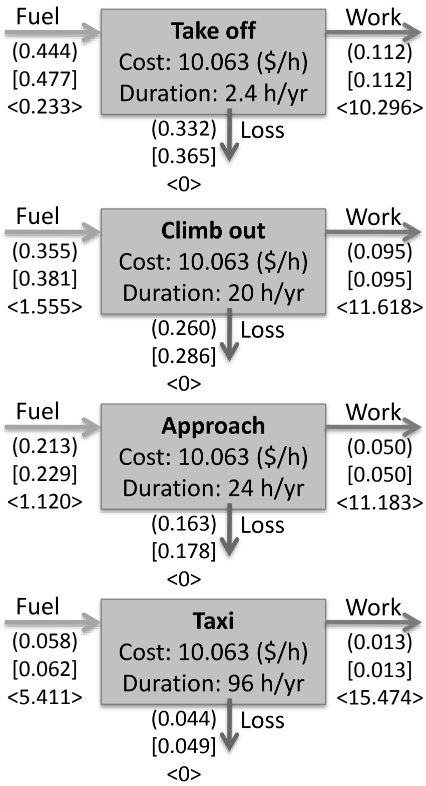

Figure 6. Energy rates (values in parentheses), exergy rates (values in square brackets) and costs (values in angle brackets) are indicated for four LTO phases. Energy and exergy rates are in MW, and cost values are in $/h.

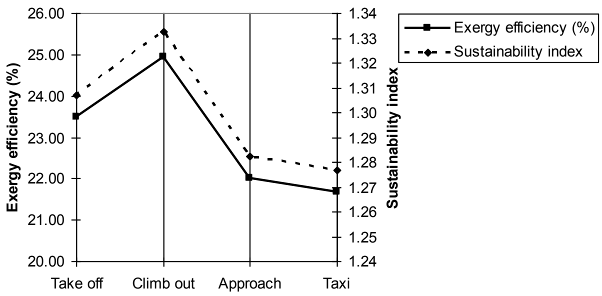

Figure 7. SI and exergy efficiency vs LTO phases.

CONCLUSIONS

We have presented the energy, exergy, exergoeconomic, EXCEM analysis and sustainability assessment of a piston-prop aircraft engine at LTO in this paper. Some concluding remarks obtained from the results of the main study may be listed as follows:

- The cruise time can change based on the assumptions made, and therefore it should be noticed that the cruise is sometimes shorter than the LTO.
- Exergy efficiency values were found to be 23.47% for the takeoff, 24.95% for the climb out, 22.02% for the approach and 21.68% for the taxi.
- The highest exergy destruction rate value was found to be at takeoff with 248.55 kW, because of the highest fuel consumption.
- Taking the PEC of a piston-prop aircraft engine as $39,000, the levelized and annualized cost of the maintenance was found to be roughly 1.05% of the CI cost.
- Takeoff phases of LTO take much of the operating costs, while taxi takes the least. This leads to high exergoeconomic factors with 98.81%.
- Because the taxi phase is a long one, it has the most exergy destruction cost rate.
- As shown in EXCEM method results, while takeoff has the most energetic and exergetic values, its cost output is the least.
- Maximum SI rate was found to be 1.332 for climb out phase, while minimum SI rate was obtained to be 1.277 for taxi. It shows that, the system based on climb out phase is more sustainable than the others, because SI is directly related with the exergy efficiency.
- In the light of the exergoeconomic and EXCEM analysis, to reduce the cost, the distance between apron and runway should be minimized for piston-prop aircraft engines.

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