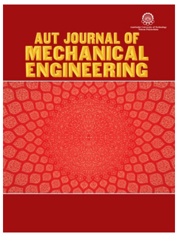

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Comparative thermoeconomic analysis of using different jet fuels in a turboshaft engine for aviation applications

V. Zare[1*], Sh. Khodaparasta[1], E.Shayan[2]

[1] Faculty of Mechanical Engineering, Urmia University of Technology, Urmia, Iran
[2] Faculty of Mechanical Engineering, Urmia University, Urmia, Iran

ABSTRACT: Fuel efficiency of helicopter and aircraft propulsion systems become more important in recent years due to the rising fuel costs and environmental impacts of aviation emissions. In this regard, in the present study, the use of three conventional types of jet fuels in a turboshaft engine is investigated from exergy and exergoeconomic viewpoints. Component-based exergy and cost calculations are accomplished by developing thermodynamic and exergoeconomic models which their accuracy is validated using the available experimental data in the literature. To examine the effects of important design/operating variables on the engine performance, a parametric study is performed for the considered fuels to assess exergy and economic performance. Also, the influence of flight altitude is investigated on the engine performance in terms of net output power, exergy efficiency, and unit cost of power. The results indicate that, JP-4 jet fuel yields better performance for considered turboshaft engine in terms of exergy efficiency and unit cost of power. It is shown that the engine exergy efficiency for JP-4 fuel is around 9 % and 6% higher than that for JP-5 and JP-8 fuels, respectively. .

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1- Introduction

A turboshaft engine is a kind of gas turbine that is designed to generate shaft power (rather than jet thrust) to drive air and sea vehicles. This type of aero engine is widely employed for applications that require large power values with a lightweight and small size. Turboshaft engines are widely used in helicopters, hovercrafts, tanks, boats and ships, and some stationary power units [1]. At present, the aviation industry consumes around 13% of transportation-related fossil fuels which accounts for about 2% of the global CO_2 emissions [2]. Air transportation is growing rapidly around the world where its growth is expected to be 5.1% annually [3].

In recent years, the aviation industry as a large fuel consumer has been given much attention to enhance the engines' performance in order to reduce the environmental problems and to improve cost performance [4]. The CO_2 emission by the aviation industry in 2036 is expected to be 2.5 times higher than in 2006 due to the increase in demand for aviation. Besides environmental problems, fuel cost is another motivation for research and development in this field since it accounts for 20-50% of direct operating costs of an aircraft [1]. Therefore, studies on fuel consumption reduction methods are of great importance. In this respect, exergoeconomic analysis is a powerful technique to evaluate and optimize energy conversion systems from both thermodynamic and economic perspectives [5]. Also, thermodynamic analyses and investigations play an important role in the evaluation of energy conversion systems, including power plants and engines. In this respect recently Lu et al. [6] conducted a thermodynamic analysis of hot syngas impurities in steel reheating furnaces. Regarding the different temperature levels of the furnaces, the thermodynamic calculations are conducted at different temperatures to predict the fate of impurities. Gonzalez et al. [7] performed energy and exergy analysis on an integrated gasification-power plant operating in the sawmill industry. From the thermodynamic analysis it was be found that cold-gas and hot-gas efficiencies close to 74.5% and 84.6% could be achieved by considering an equivalence ratio of 0.34, respectively.

During the last decade, lots of research works are focused on aero engines (including turboprop, turbofan, turbojet, and turboshaft engines) performance analysis, emissions reduction, and economic considerations. Balli et al. [8] conducted exergy and exergoeconomic analyses on J69-T25A turbojet engine and indicated an exergy efficiency of 34.84% and unit exergetic cost of exhaust gases of 70.956 US$GW^{-1}. Tona et al. [9] presented an exergy analysis for an aircraft engine to evaluate the input and output exergies and to determine the performance of engine components in each flight phase. Their results indicated a maximum exergy efficiency of 26.5% during the cruise phase, while the efficiency is decreased to 6% during landing. Exergy analysis is applied to a

*Corresponding author's email: v.zare@uut.ac.ir turbojet engine over the altitudes from sea level to 15000 m by Etele and Rosen [10], who reported an exergetic efficiency of 16.9% and 15.3% respectively at sea level and altitude of 15000 m. Ekici et al. [11] investigated the performance of a small turbojet engine with exergy analysis based on test data and found that around 55% of the fuel exergy cannot be used by the engine as the combustion chamber accounts for a major proportion of the total exergy destruction. For a small-scale turbojet engine, exergy and exergoeconomic analysis are presented by Coban et al. [12], who reported a value of 79.08 US$/h.kN for the thrust cost rate of the engine. Recently, advanced exergy analysis is applied on a military turbojet engine by Balli [13], who found that the investigated engine has a low potential for improvement as the unavoidable exergy destruction is found to be higher than 93%. In another study, he presents a sustainability analysis based on the exergy concept on a turbofan engine for take-off power operation mode [14]. For a small turbojet engine, Kahraman et al. [15] analyzed numerically the combustion characteristics of the combustor fueled by jet-A fuel and hydrogen and found that hydrogen combustion is advantageous in terms of the outlet temperature and the pressure drop as well as CO2 and unburned HC emissions.

An exergy analysis on a turbofan engine is conducted by Turgut et al. [16] , with an augmenter at sea level and an altitude of 11,000 m, who showed that the augmenter unit had the highest exergy destruction with 48.1% of the whole engine at sea level. Another turbofan engine is evaluated by Sohret et al. [17], who applied advanced exergy analysis and found that the engine has a little improvement potential due to high unavoidable exergy destruction of 93.55%. A T56 turboprop engine is investigated by Balli and Hepbasli [18] based on energy and exergy perspectives for different power loading operational modes. They concluded that the highest exergy destruction belongs to the combustion chamber and its value significantly increases with changing operation modes. In another research, they conducted exergoeconomic, sustainability, and environmental evaluations on the T56 engine and found that the unit exergetic cost of shaft power is decreased from 76.34 $/GJ at 75%-mode to 58.32 $/GJ at Takeoff-mode as a result of increasing shaft power [19]. A component-based exergetic evaluation on an experimental CT7 turboprop engine is performed by Aydin et al. [20, 21], who found that the lowest exergy destruction occurs in the gas turbine, and the exergy destruction values within all components are increased with increasing the torque value. Atılgan et al. [3] performed an environmental impact assessment using the exergy concept on a turboprop engine employed in regional aircraft with 1948 shp and 640 N.m torque. They showed that the combustion chamber, compressor, power turbine, and exhaust nozzle contribute by 69%, 9%, 7%, and 2% on the total environmental impact of the engine. The effects of reference altitudes of 4000–9000 m on the exergetic performance of a turbofan engine are analyzed by Turan [22], who reported the values of 50.34% and 48.91% for the exergy efficiency at 4000 and 9000 m altitudes, respectively. Aydın et al. [23] presented a detailed sustainability performance investigation of a turboprop aircraft engine using exergetic sustainability indicators for eight flight phases. Their results indicated a maximum exergy efficiency of 29.2%, and a maximum exergetic sustainability index of 0.41. A review of studies on exergy analysis applied for performance investigation of aircraft engines is conducted by Şöhret et al. [24].

Recently, a few studies have focused on the investigation of turboshaft engine performance. Turan and Aydın [25] conducted energy and exergy analyses on a turboshaft engine at the maximum power ratio conditions and reported an exergy efficiency of 27.5% for the engine, while the values of 83.8%, 88.6%, 80.6%, and 91.4% are calculated for the exergy efficiencies of the compressor, power turbine, combustor and gas generator turbine, respectively. Coban et al. [1] presented the energy and exergy analyses on a turboshaft engine (Makila 1A1 engine) for military helicopters for four various loads. They reported that the highest value of exergetic efficiency for the engine is 27.65% at the load value of 547 N.m. Designing and analysis of a regenerator for a turboshaft helicopter engine is surveyed by Cheeda et al. [26] for attaining high effectiveness and low-pressure drop and weight. They found that an optimal regenerator can increase the thermal efficiency of the engine by 5% and reduce the specific fuel consumption by 23%. Nkoi et al. [27] investigated simple and modified cycles for turboshaft engines used for civil helicopters and concluded that the modified cycle with unconventional components has significantly better performance than traditional simple-cycle engines in terms of efficiency and fuel consumption. In recent research on turboshaft engines, Zhang and Gümmer [28, 29] investigated the potential of incorporating efficient recuperators for helicopter turboshaft engines and concluded that the recuperated engine achieves a considerable reduction of fuel consumption under different flight conditions. They quantified the trade-offs between fuel economy improvement and weight penalty in the recuperated engine for a wide range of recuperator effectiveness [30].

Through a comprehensive review of the previous literature, it is observed that for turboshaft engines most of studies have focused on energy and exergy analysis. For these engines, any research on exergoeconomic investigation has not appeared in the open literature to the best of the authors' knowledge. Also, as the kind of jet fuel has a key role in the thermodynamic and economic performance of aero engines, the present paper aims at the investigation of a turboshaft engine performance for three kinds of jet fuels based on exergoeconomic analysis. The considered fuels have different thermal, chemical and cost characteristics. Also, the engine performance is assessed over the various flight altitudes. To simulate the engine performance, thermodynamic and exergoeconomic models are developed and to examine the influences of design/operating conditions a parametric study is conducted.

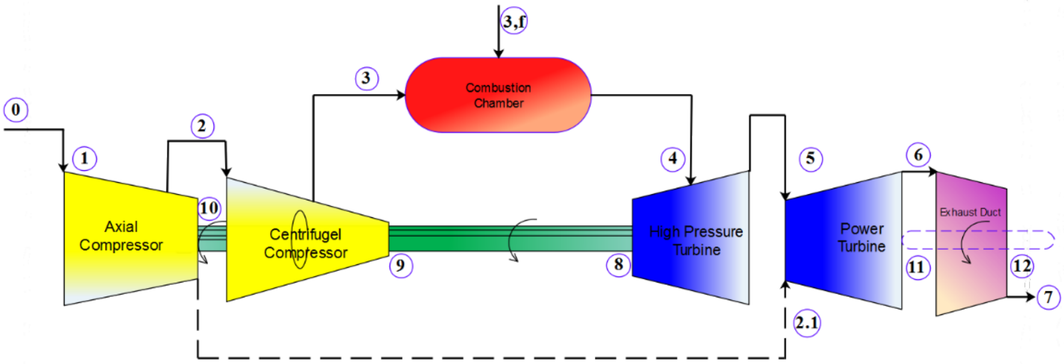


Fig. 1. Schematic view of the considered turboshaft engine

Table 1. Fuel characteristics [24, 32]

Fuel	Chemical formula	LHV (kJ/kg)	Price ($/kg)
JP-4	$C_{8.5}H_{17}$	43010	2.85
JP-5	$C_{12}H_{22}$	43412.5	2.79
JP-8	$C_{12}H_{23}$	42800	3.13

2- System Description and Assumptions

A turboshaft engine consists of two parts: the gas generator and the power section. The gas generator itself is made up of a compressor, combustion chamber, and normally one stage of high-pressure turbine, while the power section consists of additional turbine stages and the shaft output. The hot gases exiting the gas generator drive the power section. In most engine designs, the power section and gas generator are mechanically separate to be able to rotate at appropriate different speeds for various conditions [31].

Schematics of the considered turboshaft engine in this study is illustrated in Fig. 1 that is a Makila 1A1 engine. As shown in Fig. 1, the main engine components are centrifugal/axial compressors, combustor, High-Pressure Turbine (HPT), Power Turbine (PT), and exhaust duct. The environmental air (stream 1) is taken into the engine and is pressurized by the compressors. A large amount of pressurized air by the axial compressor flows through the engine core (stream 2) and is more compressed by the centrifugal compressor, then is combusted by the fuel and generates hot gases (stream 4) which pass through the HPT. The remaining part of compressed air (stream 2.1) by the axial compressor (the bypass flow) is mixed with the hot gases exiting the HPT at the entry of the PT. The hot gases (stream 5) are expanded through the PT and the shaft power is generated. The exiting gas stream from the PT (stream 6) is exhausted through the exhaust duct (stream 7).

To model the performance of the considered turboshaft engine, the following assumptions are made [1]:

a) The engine works under steady-state conditions.
b) The changes in kinetic and potential energy and exergy within the engine are assumed to be negligible.
c) The air and combustion gas mixture are assumed to behave as ideal gases.
d) The pressure loss through the combustion chamber is assumed to be 5%.
e) The combustion reaction is assumed to be complete combustion.
f) The environmental air is assumed to be a composition of 77.48% N_2, 20.59% O_2, 0.03% CO_2, and 1.90% H_2O.
g) The engine components are assumed to be adiabatic and the compressors and turbines work with appropriate values of isentropic efficiencies as given in Table 4.

In the present study as mentioned above, three kinds of jet fuels are considered and their influences are investigated on the engine performance in terms of thermodynamics and economics. The specifications of these fuels are outlined in Table 1. The considered fuels are made up of 65% diesel and 35% oil. Their storage conditions and appearance are the same. They differ only in the pressure of evaporation and the ignition point. For example, JP-8 fuel has a higher ignition point and fewer carcinogenic compounds.

3- Modeling and Analysis

For performance modeling of the considered turboshaft engine, computer programs are developed using the EES software. For such thermodynamic modeling, each engine component is considered as a control volume for which are applied the principle of mass conservation as well as the first and second laws.

3- 1- Energy and Exergy analysis

To perform the energy analysis on the considered engine, mass conservation and the first law of thermodynamics would be applied to its components. Under the steady-state operating conditions for a control volume, mass and energy balance equations yield their conservation as:

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

$$\dot{Q} + \sum \dot{m}_{in} h_{in} = \dot{W} + \sum \dot{m}_{out} h_{out} \tag{2}$$

Assuming a complete combustion between the fuel and air entering the chamber, the following combustion reaction for a hydrocarbon fuel can be applied:

$$\lambda C_n H_m + \left\{ \begin{matrix} 0.7748N_2 \\ +0.2059O_2 \\ +0.0003CO_2 \\ +0.019H_2O \end{matrix} \right\} \rightarrow \tag{3}$$

$$\left(x_{CO_2} CO_2 + x_{H_2O} H_2O + x_{O_2} O_2 + x_{N_2} N_2 \right)$$

where, λ is the number of fuel moles for 1 mole of air.

In addition to the energy analysis, the exergy analysis based on the second law of thermodynamics is an important technique to assess the performance of energy-related systems. Exergy, as the maximum attainable work from a system/fluid stream, can be divided into four parts, two of which (kinetic and potential terms) are usually negligible. The physical exergy for a fluid stream is defined as [33]:

$$\dot{Ex}_{ph} = \dot{m}\left[\left(h - h_0\right) - T_0\left(s - s_0\right)\right] \tag{4}$$

The chemical exergy, for ideal gas mixtures, is defined as [34]:

$$\dot{Ex}_{ch,i} = \dot{n}_i \left[\sum_i x_i ex_{0,i} + \bar{R} T_0 \sum_i x_i \ln x_i \right] \tag{5}$$

Also, chemical exergy of the liquid fuels can be expressed as follows [1]:

$$\frac{ex_{ch,f}}{\dot{m}_f LHV} = \varnothing = 1.0401 + 0.01728\frac{h}{c} + \\ 0.0432\frac{o}{c} + 0.2196\frac{s}{c}\left(1 - 2.0628\frac{h}{c}\right) \tag{6}$$

In which, *s, o, c,* and *h* denote the mass fractions of sulfur, oxygen, carbon, and hydrogen, respectively. The sulfur is usually negligible due to its nearly zero fraction in the composition of fuel [35].

The exergy balance equation for the engine components can be expressed as follows to assess the exergy destruction within a component [36]:

$$\dot{Ex}^{Q} + \sum \dot{Ex}_{in} = \dot{Ex}^{W} + \sum \dot{Ex}_{out} + \dot{Ex}_{D} \tag{7}$$

where, $\sum \overset{ÿ}{Ex}_{in}$ and $\sum \overset{ÿ}{Ex}_{out}$ denotes the total input and output exergies by flow streams.

To simulate the performance of the considered engine, the energy- and exergy-related equations as listed in Table 2 are introduced into the computer program.

A rational criterion for performance evaluation from the second law perspective is the exergy efficiency. For the considered turboshaft engine, it is defined as:

$$\eta_{ex} = \frac{\dot{Ex}_{out}}{\dot{Ex}_{in}} = \frac{\dot{W}_{net,out}}{\dot{m}_{fuel} ex_{fuel}} \tag{8}$$

3- 2- Exergoeconomic analysis

Developing new strategies for the investigation of energy conversion systems has been gained more attention over recent years. The strategies mainly are focused on the efficient

Table 2. Relations applied to model the engine performance [1, 37]

Component	Energy equation	Exergy balance equation
Axial Compressor (AC)	$\eta_{ac}=\frac{h_1-h_{2,s}}{h_1-h_{2,a}}$ $\dot{W}_{ac}=\dot{m}_2\left(h_2-h_1\right)$	$\dot{E}x_1+\dot{W}_{10}-\left(\dot{E}x_2+\dot{E}x_{2,1}\right)=\dot{E}x_{D,AC}$
Centrifugal Compressor (CeC)	$\eta_{cec}=\frac{h_2-h_{3,s}}{h_2-h_{3,a}}$ $\dot{W}_{cec}=\dot{m}_3\left(h_3-h_2\right)$	$\dot{E}x_2+\dot{W}_9-\dot{E}x_3=\dot{E}x_{D,CeC}$
Combustion chamber (CC)	$\dot{m}_3h_3+\dot{m}_fLHV=\dot{m}_gh_4+\left(1-\eta_{cc}\right)\dot{m}_fLHV$	$\dot{E}x_3+\dot{E}x_{3,f}=\dot{E}x_{D,CC}$
High-pressure turbine (HPT)	$\eta_{hpt}=\frac{h_4-h_{5,a}}{h_4-h_{4,s}}$ $\dot{W}_{hpt}=\dot{m}_g\left(h_4-h_5\right)$	$\left(\dot{E}x_4-\dot{E}x_5\right)-\dot{W}_{HPT}=\dot{E}x_{D,HPT}$
Power turbine (PT)	$\eta_{pt}=\frac{h_5-h_{6,a}}{h_5-h_{6,s}}$ $\dot{W}_{pt}=(m_g+\dot{m}_{2,1})\left(h_5-h_6\right)$	$\left(\dot{E}x_{2,1}+\dot{E}x_5-\dot{E}x_6\right)-\dot{W}_{PT}=\dot{E}x_{D,PT}$
Exhaust duct (ED)	$\eta_{ED}=\frac{h_6-h_{7,c}}{h_6-h_{7,s}}$	$\dot{E}x_6+\dot{E}x_7=\dot{E}x_{D,ED}$

utilization of fuels and heat sources from the viewpoints of both thermodynamics and economics. Despite the fact that exergy analysis is a useful technique to identify the sources of real inefficacies in a thermodynamic system, however, an economic investigation is vital to design a cost-effective system. Such an investigation and design can be fulfilled by the exergoeconomic analysis [38]. The aim of an exergoeconomic analysis is to optimize the system performance regarding both the exergetic criterion and the cost figures. Using this approach, the designer is provided with useful and cost-effective information which is not accessible through regular exergy or economic evaluations. The actual cost of system products is an important outcome of the exergoeconomic analysis [39].

In an exergoeconomic analysis, cost balance equations with appropriate auxiliary relations are applied to each component in order to assess the cost rate of each exergy stream. Having known the cost rate of exergy streams, their unit costs in $/GJ can be calculated. The overall cost balance equation for a component that receives thermal energy and generates power can be expressed as [40, 41]:

Table 3. The cost functions, cost balances, and auxiliary relations

Component	Cost balance and auxiliary equation	Cost function
Axial Compressor (AC)	$\dot{C}_{2,1}+\dot{C}_{2}=\dot{C}_{1}+\dot{C}_{\dot{W}_{ac}}+\dot{Z}_{AC}$ $c_1=0$	$\left(\frac{71.1\dot{m}_a}{0.9-\eta_{is}}\right)\left(\frac{P_2}{P_1}\right)ln\left(\frac{P_2}{P_1}\right)$
Centrifugal Compressor (CeC)	$\dot{C}_{3}+\dot{C}_{\dot{W}_{ac}}=\dot{C}_{2}+\dot{C}_{\dot{W}_{cec}}+\dot{Z}_{CEC}$ $c_2=c_{2,1}$	$\left(\frac{71.1\dot{m}_2}{0.9-\eta_{is}}\right)\left(\frac{P_3}{P_2}\right)ln\left(\frac{P_3}{P_2}\right)$
Combustion chamber (CC)	$\dot{C}_{4}=\dot{C}_{3}+\dot{C}_{3,f}+\dot{Z}_{CC}$	$\left(\frac{46.08\dot{m}_f}{0.995-\frac{P_4}{P_3}}\right)\left(1+\exp\left(0.018T_4-26.4\right)\right)$
High-pressure turbine (HPT)	$\dot{C}_{5}+\dot{C}_{8}=\dot{C}_{4}+\dot{Z}_{hpt}$ $c_5=c_4$	$\left(\frac{479.34\dot{m}_g}{0.92-\eta_{is,gt}}\right)ln\left[\frac{P_4}{P_5}\right]\left(1+\exp\left(0.036T_4-54.4\right)\right)$
Power turbine (PT)	$\dot{C}_{6}+\dot{C}_{\dot{W}_{pt}}=\dot{C}_{5}+\dot{C}_{2,1}+\dot{Z}_{pt}$ $c_8=c_{10}$ $c_9=c_8$	$\left(\frac{479.34\dot{m}_g}{0.92-\eta_{is,gt}}\right)ln\left[\frac{P_5}{P_6}\right]\left(1+\exp\left(0.036T_5-54.4\right)\right)$

$$\sum\dot{C}_{out,k}+\dot{C}_{w,k}=\sum\dot{C}_{in,k}+\dot{C}_{q,k}+\dot{Z}_{k} \tag{9}$$

$$\dot{C}_{i}=c_{i}\dot{E}x \tag{10}$$

where, c is the exergetic unit cost of the stream and $\dot{E}x$ denotes the exergy rate.

In Eq. (9), $\dot{Z}_k$ is associated cost rate with capital investment and OM costs for k the th component as follows [42]:

$$\dot{Z}_{k}=\dot{Z}_{k}^{CI}+\dot{Z}_{k}^{OM} \tag{11}$$

The capital cost of a system component can be converted to the corresponding cost rate using the Capital Recovery Factor (*CRF*) and the maintenance factor (φ) by the following relation [33]:

$$\dot{Z}_{k}=\frac{Z_{k}.CRF.\varphi}{N} \tag{12}$$

where N is the annual operating hours of the system.

The *CRF* is expressed as a function of interest rate, i_r and the system useful life, n as [33]:

$$CRF=\frac{i_r\left(1+i_r\right)^n}{\left(1+i_r\right)^n-1} \tag{13}$$

Table 4. Input data [1, 9]

Parameter	Symbol	Value
Turbine isentropic efficiency	η_T (%)	85
Compressor isentropic efficiency	η_c (%)	85
Reference temperature	T_0 (K)	288.15
Reference pressure	P_0 (kPa)	92
Turbine inlet temperature	TIT (K)	1090.15
Compressor pressure ratio	r_P	7.3
Combustion chamber efficiency	η_{cc} (%)	98
Mechanical efficiency	η_{mech} (%)	97
Exhaust duct efficiency	η_{ED} (%)	99
Interest rate	i (%)	8
Operating hours	τ (h/yr)	800
Engine lifetime	n (yr)	30

The cost balances and auxiliary equations for the components of the considered turboshaft engine are outlined in Table 3.

The input data and values of variables used in evaluations of the turboshaft engine in this study are given in Table 4.

The flowchart of the system modeling and problem solution is illustrated in Fig. 2.

4- Results and Discussion

Before presenting the results, a model validation would be appropriate to reveal the accuracy of developed models and simulation procedures. Such validation is accomplished by comparing the results of the present model with experimental results obtained by Kahraman et al. [1] for the considered turboshaft engine. The comparison is shown in Table 5 which indicates a good agreement between the calculated values of the parameters in this work with those obtained by experimental tests. The source of the small discrepancies between the two sets of results is due to some minor differences in modeling assumptions and approaches with the experimental setup operation.

4- 1- Results of parametric study

In order to evaluate the turboshaft engine performance from thermodynamics and exergoeconomics points of view, the above-mentioned equations along with thermodynamic property relations are introduced into a computer program developed by EES software. A parametric study is carried out to compare using different jet fuels and to examine the influence of key operating/design variables on engine performance. The compressor pressure ratio, high-pressure turbine inlet temperature, and flight altitude are considered important operating/design variables. The effects of these variables are investigated on the engine performance in terms of exergy efficiency (η_{ex}), net output power ($\dot{W}_{sp} = \dot{W}_{net}$) and unit cost of the product (unit cost of shaft power, c_P).

The compressor pressure ratio can be considered as the main design variable, the effects of which are shown in Figs. 3(a–c) on the engine performance. Referring to this figure, using JP-4 as the jet fuel results in a higher exergy efficiency and lower cost of power, while it yields negligible lower output power compared to the other fuels. This trend can be mainly attributed to the fuel characteristics (chemical formula, LHV,

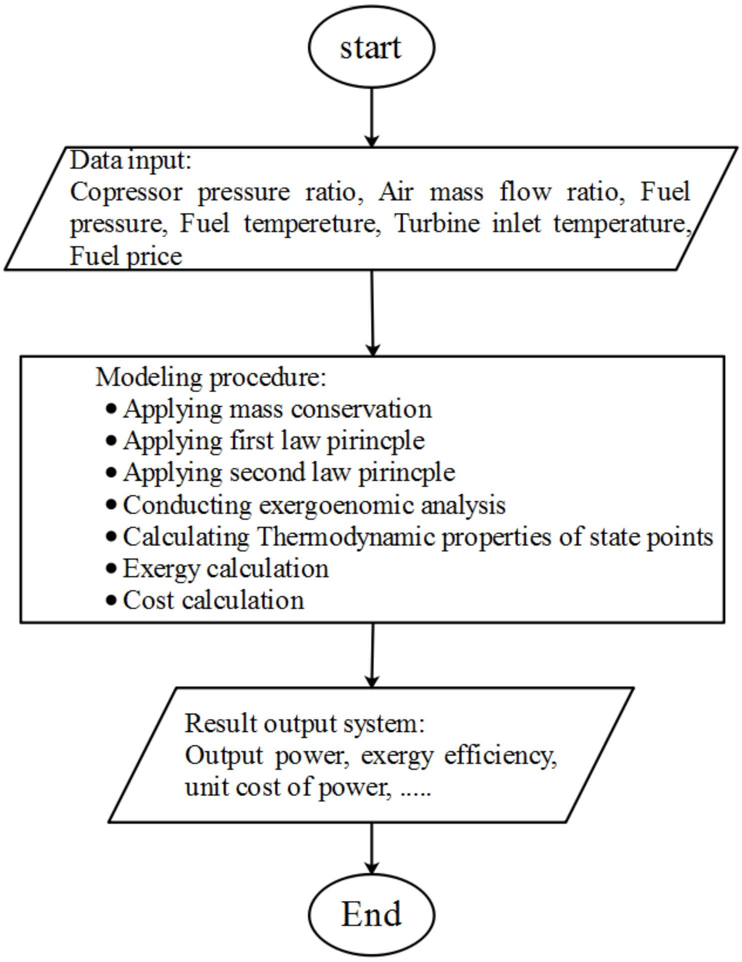


Fig. 2. Flowchart of the problem solution

and price) as given in Table 1. Despite a slight lower power generation by JP-4 compared to JP-5 (as shown in Fig. 3(a)), the higher η_{ex} obtained for JP-4 compared to JP-5 (as shown in Fig. 3(b)) is due to its lower LHV and hence lower chemical exergy which is entered into the engine. Also, it is important to note that, different chemical formulas for the considered fuels brings about different values of fuel mass flow rate entering the combustion chamber, which can be considered as another important factor affecting the engine thermodynamic and economic performance, as the unit price of JP-8 is significantly higher than JP-5 (Table 1), however, the unit cost of generated power by the engine is lower for the case of JP-8 compared to JP-5 as shown in Fig. 3(c).

The effects of high-pressure turbine inlet temperature on the engine performance are shown in Figs. 3(a–c). The figure indicates significantly higher net power and efficiency values as well as lower cost unit values for higher turbine inlet temperatures, as expected. Also, Figs. 3(b,c) indicate better performance of JP-4 fuel in terms of efficiency and unit cost of power compared to the other considered fuels for all the considered range of TIT. Fig. 3(b) reveals for JP-4 fuel that, as the TIT increases from 1000 to 1400 K the exergy efficiency increases from 25.98 to 31.33 % as a result of which the unit cost of power is decreased from 75.7 to 70.5 $/GJ as shown in Fig 3(c).

Figs. 4(a–c) shows the effects of compressor pressure ratio at different turbine inlet temperatures on the unit cost of power. Referring to this figure, for higher turbine inlet temperatures the unit power cost would be minimized at higher compressor pressure ratios. Also, the figure confirms that as mentioned above, higher TITs result in a lower cost of power values which is due to the higher output power and efficiency. Also, the figure reveals that the unit power cost values dramatically high at lower pressure ratios than around 5 for all the fuels and TITs.

As another important parameter affecting the performance of aircraft engines is the flight altitude, the effect of which is widely investigated in literature especially for cylindrical engines. Figs. 5(a–c) shows the effect of flight altitude on the engine performance in terms of net output power, exergy efficiency, and unit cost of power. To investigate the effects

Table 5. Comparison between the results of the present study with experimental test results

Kahraman et al. [1]					present work				Errors (%)			
Stream	Mass flow rate(kg/s)	Temperature (K)	Pressure (kPa)	Exergy (kW)	Mass flow rate (kg/s)	Temperature (K)	Pressure (kPa)	Exergy (kW)	Mass flow rate	Temperature	Pressure	Exergy
0	0.00	288.15	92.00	0.00	0.00	288.15	92.00	0.00	0	0	0	0
1	4.54	288.15	92.00	0.00	4.54	288.15	92.00	0.00	0	0	0	0
2	4.44	410.16	264.28	484.07	4.44	410.4	264.5	488.5	0	0.05	0.083	0.9
2,1	0.09	410.16	264.28	9.81	0.09	410.4	264.5	9.939	0	0.05	0.083	1.3
3	4.44	546.64	669.85	1078	4.44	547	670	1088	0	0.06	0.022	0.92
3,f	0.06	288.15	220.00	2985.7	0.057	288.15	220.00	2985	5	0	0	0.02
4	4.51	1090.15	637.12	2893.91	4.496	1090	637.8	2927	0.51	0	0.1	1.16
5	4.51	863.15	215.44	1635.12	4.496	863.4	215.2	1641	0.51	0.03	0.11	0.35
6	4.6	722.23	97.44	889.04	4.587	722.5	97.46	885.4	0.28	0.037	0.02	0.41
7	4.6	711.69	92.00	834.59	4.587	712.6	92	831.5	0.28	0.12	0	0.37

of this parameter on the engine performance the following relations for ambient temperature and pressure are used [43]:

$$T_{amb} = 288.15 - 0.0065h$$

$$P_{amb} = 92.0\left(\frac{288.15}{T_0}\right)^{-5.25588} \qquad h < 11000\,\mathrm{m} \qquad (14)$$

$$T_{amb} = 216.67$$

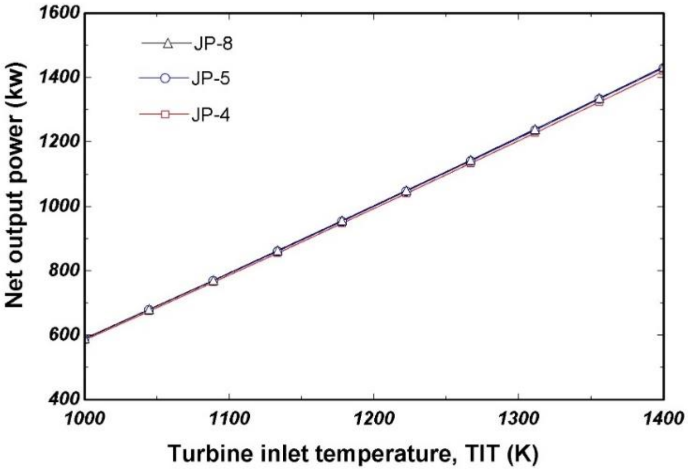
$$P_{amb} = 22.63253/\exp\left(0.000157689h - 10998.1\right) \quad (1)$$

$$11000\,\mathrm{m} < h < 24000\,\mathrm{m}$$

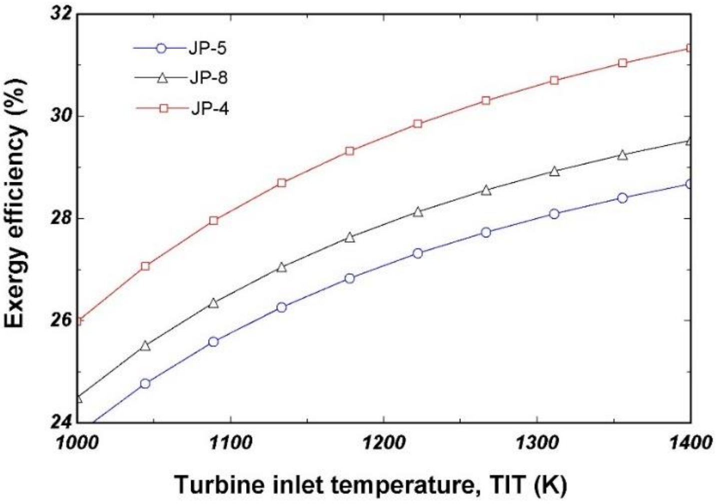
Referring to Fig. 5(a), it can be seen that as the flight altitude increases the net output power is decreased. This is due to the fact as the flight altitude raises the ambient air becomes less dense and thus for a given volumetric flow rate of air entering the engine, the amount of air mass flow rate and generated power would be reduced. Figs. 5(b–c) indicate that the engine performance deteriorates significantly at higher flight altitudes in terms of exergy efficiency and unit power cost, as a result of less power generation at higher altitudes. The lower efficiency values at higher altitudes have two reasons; the first one is the decreased output power as explained above and the second one is burning more fuel to provide the required shaft power at higher altitudes. The reduced output power and efficiency are responsible for increasing of the unit cost of power at higher altitudes as shown in Fig. 5(c).

5- Conclusions

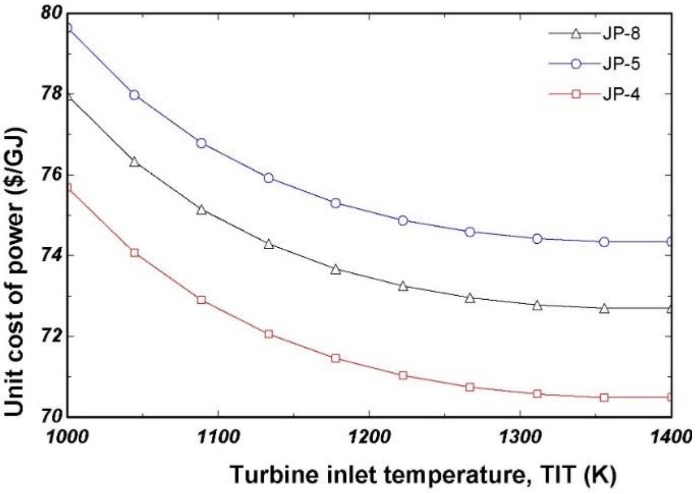
Comparative exergy and exergoeconomic investigation are reported of using three kinds of conventional jet fuels in a Makila 1A1 turboshaft engine used in helicopters. Comprehensive analyses of design/operating variables are performed on the engine performance in terms of unit power cost, output power, and exergetic efficiency, and important insights are yielded to the engine operation. The methodology and results of the present paper could be beneficial to lead improvement investigations on such turboshaft engines and be valuable in the development and design of similar turboprop/turboshaft propulsion systems.



(a)

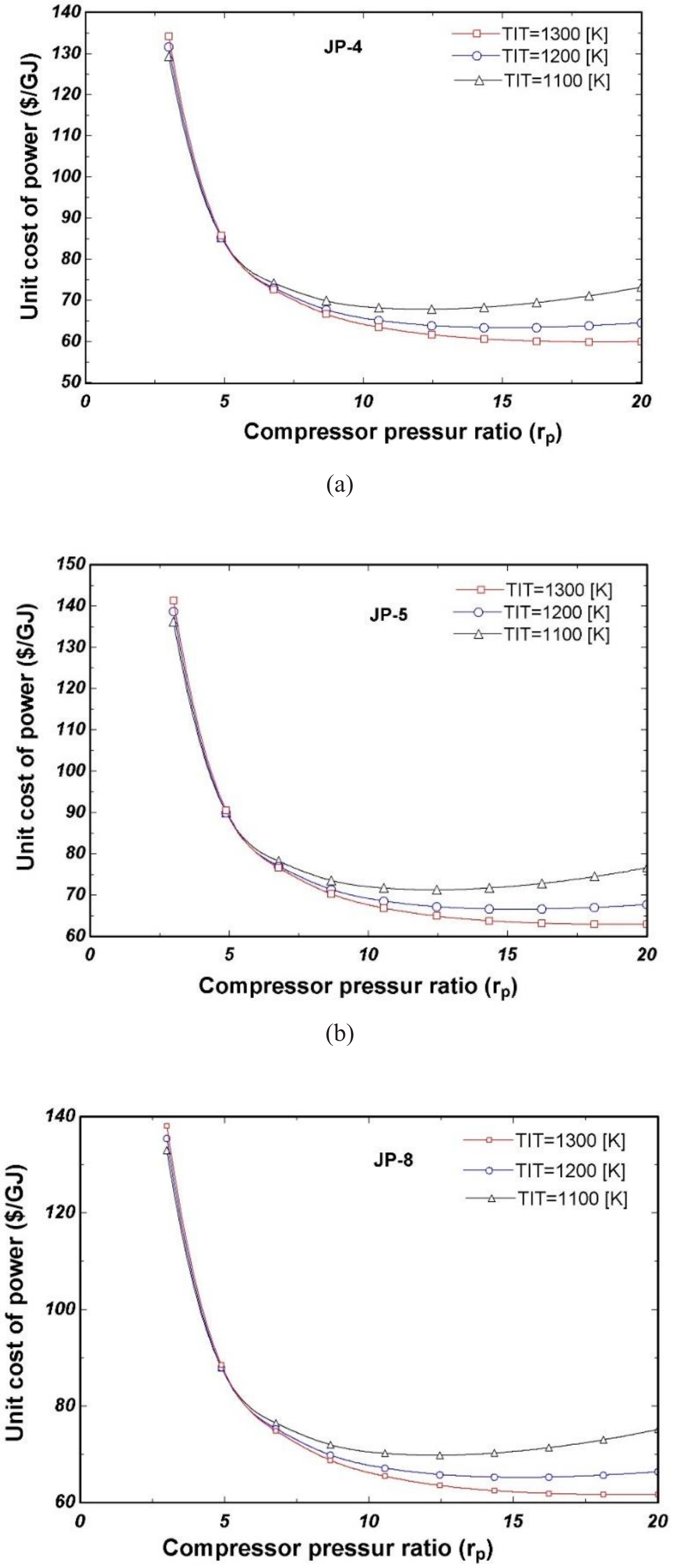


(b)



(c)

Fig. 3. Effects of turbine inlet temperature on the performance of turboshaft engine for different fuels at sea level

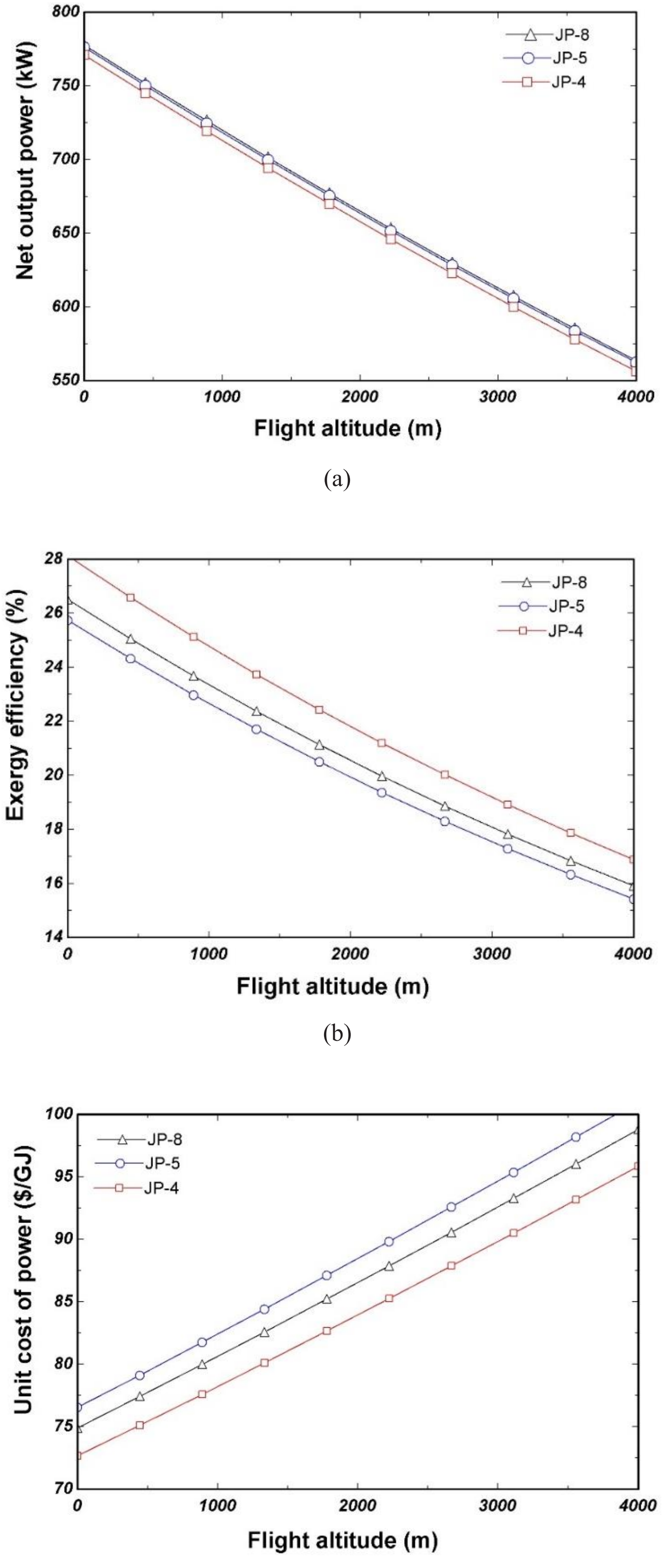


(a)

(b)

(c)

Fig. 4. Effects of compressor pressure ratio at different turbine inlet temperatures on the unit cost of power at sea level



(a)

(b)

(c)

Fig. 5. Effects of flight altitude on the performance of turboshaft engine for different fuels

The main conclusions of this paper can be listed as follows:

- For all the practical range of operating conditions, JP-4 fuel yields higher exergy efficiency and lower unit cost of power than the JP-5 and JP-8 fuels.
- A negligible difference is detected between the values of net output power for the three considered fuels.
- The engine performance deteriorates significantly at higher flight altitudes in terms of exergy efficiency and unit cost of power.
- With increasing the turbine inlet temperature, the exergy efficiency increases as well and the unit cost of power decreases.
- Increasing the compressor pressure ratio results in a decrease of the unit cost of power at first then brings about an increase of unit power cost. As a result, there is an optimal value for compressor pressure ratio at which the unit power cost would be minimized.
- As the flight altitude increases, the exergy efficiency of the engine decreases and the unit cost of engine power increases.

Nomenclature

AC	Axial Compressor
CeC	Centrifugal Compressor
CC	Combustion chamber
COD	Cost optimal design
CRF	Capital recovery factor
ED	Exhaust duct
HPT	High-pressure turbine
PT	Power Turbine
LHV	Lower heating value (kJ kg^{-1})
c	Unit cost of exergy ($/GJ)
$\dot{C}$	Cost rate of exergy streams
Ex	Exergy (kJ kmol^{-1})
h	Enthalpy (kJ kmol^{-1}K^{-1})
Q	Heat rate (kW)
P	Pressure (kPa)
POD	Power optimal design
T	Temperature (°C)
s	Entropy (kJ kmol^{-1}K^{-1})
W	Power (kW)
Z	Investment cost ($)

Subscripts

0	Reference state
ch	Chemical
CI	Capital investment
ex	Exergetic
D	Destruction
OM	Operation and maintenance
P	Power, pressure
ph	Physical
sp	Shaft power
Greek letters	
η	Efficiency

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