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Environmental impact assessment of a turboprop engine with the aid of exergy

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ABSTRACT

To develop approaches that effectively reduce engine environmental effect of aircrafts, it is necessary to understand the mechanisms that have enabled improvements in thermodynamic efficiency of aircraft engines. In the present work, a turboprop engine used in regional aircrafts that produces 1948 shp and 640 N.m torque is examined using exergo-environmental method. The results show compressor, combustion chamber, gas generator turbine, power turbine and exhaust nozzle create 9%, 69%, 13%, 7%, 2% of total environmental impact of the engine, respectively. According to rates, the compressor and gas turbine can be considered first to improve in case of component related environmental impact. Furthermore, total component related environmental impact for the turboprop engine is found to be 2.26 mPts/s for the constructional phase and 2.34 mPts/s for the operation/maintenance phases. Accordingly, it is suggested that, in order to estimate environmental impact metric of aircrafts, the exergo-environmental analysis can be employed for aircraft propulsion systems.

1. Introduction

Passenger traffic in aviation sector around the world will grow 5.1% annually. This growth will require new aircrafts and more flights. Moreover, consequences of the passenger traffic growth are a significant escalation in harmful jet engine emissions, unprecedented traffic jams, nonstop noise around the airports, and negative effects on people health and their quality of life. In order to eliminate as much potential harm to the environment as possible and make air transportation more efficient, scientist must closely work with government and industry on green and sustainable aviation initiatives [1–6].

Aviation is responsible for approximately 2% of total global greenhouse gases (GHG) emissions. This contribution is a result of 2–3% of total fossil fuel consumption worldwide. If the current growth rate of air travel continues, this trend is forecast to grow to around 3% by 2050 [7].

During last decade a lot of studies are also focusing on the aircraft emissions impact on local and regional air quality in the vicinity of airport. Aircraft (during approach, landing, taxi, take-off and initial climb of the aircraft, engine run-ups, etc.) is the dominant source of air pollution at airport. According to inventory results the part of adverse exhausts from aircraft is 50% of the total mass of emissions in the airport area. Currently the basic objects of attention are NO_x and fine particle matter (PM) emissions from aircraft engine emissions as initiators of photochemical smog and regional haze, which further direct impact on human health. Significant concerns regarding regional air pollution around the airports remain especially for city airports, which are quite closely located to habitation area, so impact of aircraft emissions on urban air quality is high. Air transport GHG, NO_x and PM emissions could be lowered by reducing activity, improving the energy efficiency of transport modes [8–10]. The aviation industry has successfully made consistent, continued efforts to reduce the fuel burn, emissions and noise produced by aircrafts. To reduce environmental impacts of aircrafts, GHG, NO_x and PM emissions should be minimized and that can be accomplished by maximizing the energy efficiency of aircraft propulsion systems [11].

Energy is an important tool for the sustainable environment. The importance of energy efficiency for green aviation is also linked to environmental problems, such as global warming, noise and atmospheric pollution [12,13]. Therefore, energy consumption plays a crucial role to achieve green aviation development. Energy efficiency is a useful metric for evaluating aircraft environmental

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performance. Moreover, technology has a vital role to play in mitigating the environmental impacts of air transport. If so, the most direct way for an airline to improve its fuel efficiency with new aircraft and its components incorporating the latest available technology [14–16]. Technical measures as aircraft and engine technology improvements have much potential for reducing emissions. The latest aircraft and engine designs are significantly more fuel efficient than previous generations of aircraft (on average, a 1–2% fuel efficiency improvement per annum). However, due to the average (economic) lifetime of 20–30 years of an aircraft the full benefit of current new engine and aircraft technology will take decades. With the possible exception of Fisher–Tropsch fuel, the development and widespread use of alternative fuels may also take decades. Therefore, the potential usefulness of energy analysis for aircraft engines in addressing environmental issues is substantial [17–22].

Energy and exergy concepts have been utilized to ensure the environmental sustainability. In order to reduce the negative impacts created by the pollutant emissions, the energy sources should be efficiently utilized. There are two environmental considerations incorporated with environment and thermodynamics: energy and exergy analysis [18]. Exergy as the thermodynamic departure between a substance and its surrounding has been gradually accepted as a unified measure for the environmental impact of waste emissions [23–25]. Wall [26] suggested exergy as a suitable measure of environmental impact of waste emissions. There have been various assessment used for waste gases emitted from transportation sectors [27,28]. The exergy of an emission to the environment, therefore, is a measure of the potential of the emission to change or impact the environment. These points suggest that exergy may be an effective indicator of the potential of an emission to impact the environment [21].

Growing focus on emissions and noise along with high fuel prices are favouring turboprops demand growth. In 2010 there were 2080 turboprops in service with an average age of 15 years. By 2030, a total of 2440 new turboprops will be delivered and the total turboprop fleet will increase to 3295 aircraft. From 2011 to 2030, a total of 660 new turboprops will be delivered: 41% to replace old aircraft and 59% to support market growth [29]. Between 2010 and 2029, Embraer forecasts that 32% of aircraft deliveries in the 30–120 seat range will be turboprops and Bombardier forecasts that 39% of aircraft deliveries in the 20–99 seat range will be turboprops [30]. The latest technology turboprops will remain an essential part of the world's regional aircraft fleet. The high fuel prices have highlighted one of the principal benefits of the twin turboprop over the regional jet: its low fuel consumption and unrivalled economics on short-haul connections. Since turboprops are more fuel efficient, increasing fuel prices could diminish the importance of passenger preference [22]. Turboprop usage on short-haul flights may increase due to a move to more fuel efficient technologies [31]. By using turboprop engines on an aircraft, the following advantages are yielded: (a) the engine can be run under more efficient and economical conditions at low and medium altitudes; (b) the amount of power available for propulsion is largely independent of the forward speed of the aircraft.

In this regard, the scientists, researchers, and engineers, who work on useful solutions for the aircraft gas turbine engines, aim at maximizing the energy saving, minimizing the energy consumption, and thus, developing the environmentally benign propulsion systems, which is reducing environmental impacts for sustainable aviation. If so, in terms of the second-law of thermodynamics, minimizing irreversibilities in the turboprop engines also becomes significant challenge for better efficiency, environment and sustainability.

Under these important considerations, a detailed literature review has been performed on exergy analysis [32,33]. The exergy studies related to gas turbine engines have been done on stationary gas turbines before. In the literature, the various exergy and exergoeconomic analysis of aero engines have been reported [31,34–44]. In terms of exergy analysis of the turboprop engines, Aydın et al. [31,34] examined some exergetic aspects of the CT7 engine. Aydın et al. [31] measured and calculated operating mass flow rates, inlet and outlet temperatures and pressures, work and power of the turboprop engine and its components. Nevertheless, exergo-environmental analyses have not been developed for turboprop engines.

Exergo-environmental analysis is a relatively new method, but it is widely used to assess environmental impact of numerous energy conversion systems. Altuntas et al. [45] investigated exergo-economic performances of piston-prop aircraft engines during landing and take-off phases of a flight. Ahmadi and Dincer [46] analyzed a gas turbine power plant, developed a simulation code and validated this code with comparing actual data obtained from a running gas turbine power plant. After optimization studies, they reported about 50.50% decrease in environmental impacts of the plant. Boyano et al. [47] examined a steam methane reforming reactor for hydrogen production, and performed both conventional and advanced exergo-environmental analysis. They also reported that environmental impact is the highest where chemical reaction occurs [48]. Meyer et al. [49] presented general methodology of exergo-environmental analysis and investigated a high-temperature solid oxide fuel cell (SOFC). Furthermore, they pointed out limitations of life cycle assessment (LCA) as an environmental assessment method. Ahmadi et al. [50] carried out an exergo-environmental analysis of a trigeneration system with a micro gas turbine engine. Petrakopoulou et al. [51] analyzed a combined cycle power plant and expressed that advanced exergy-based methods should be performed beside conventional ones to get the most accurate results. Altuntas et al. [52] investigated a piston-prop aircraft engine for four different flight phases (take-off, climb, approach and taxi). They proposed best air-to-fuel ratio/altitude/power setting option that minimizes environmental impact. Restrepo et al. [53] presented an exergetic and environmental analysis of a pulverized coal power plant located in Brazil. They also reported that highest environmental impact rate is caused by power plant as a result of highest exergy destruction rate (95.6% of overall exergy destruction of operation phase). Ahmadi and Dincer [54] modeled a combined heat and power (CHP) plant and performed exergo-environmental optimization of the plant. Results showed that higher isentropic efficiency of compressor and gas turbine causes less exergy destruction in compressor and gas turbine. This means lower fuel consumption, thus lower environmental impact and lower operating cost.

As can be seen in aviation sector, no study about exergo-environmental analysis of a turboprop aircraft engine is appeared in the open literature and that is the main motivation for the authors. In this study, exergo-environmental analysis is chosen as a method to evaluate environmental performance of an aircraft turboprop engine. Lack of exergo-environmental aspect of the turboprop engine emphasizing the originality of this article is the motivation behind this study.

In summary, this work including important exergo-environmental parameters of the turboprop engine at maximum power setting, aims to contribute to:

- determine component related environmental impacts of each turboprop engine components,
- calculate environmental impacts for each engine components result from exergy destructions,
- determine total environmental impacts of the engine components individually,

- evaluate environmental performance of the turboprop engine and its components by calculating exergo-environmental variables.

2. System description

Engines that provide the shaft power required to drive the propeller from gas turbine engine can be defined as turboprop engine [55]. A turboprop engine produces two kind of thrust, first one is generated by propeller and the other one is through the exhaust gases. The thrust generated by propeller constitutes almost 85% of the total thrust while the remaining 15% is generated by jet engine core [56]. For better understanding the main operating principle and the main roles of the turboprop engine components, Fig. 1 is illustrated. Main components of the turboprop engine shown in this figure are axial/centrifugal compressor, combustor, gas generator turbine, power turbine and exhaust. The engine studied here can either be tested by its propeller and propeller gearbox or by dynamometer instead of propeller and propeller gearbox. The air is first taken through the bell mouth assembly. The free power turbine is connected to water brake dynamometer spline through the power turbine shaft so the power turbine rotates along with dynamometer shaft. The torque and power turbine speeds are calculated by engine and dynamometer sensors as well, these values are compared all along the test. The torque transferred by the power turbine shaft of the turboprop engine is accurately measured by detecting the angular deflection of the shaft and providing an electrical signal which is representative of the deflection [31]. To develop the exergo-environmental analysis of the turboprop engine, the first step should be to perform the exergy analysis of the engine. Actually, the main objective of this study is not to perform an exergy analysis for a turboprop engine. Such an analysis and more details on the turboprop engine can be found in the literature [31,34]. Parameters of the turboprop engine and its environment are given in the Table 1 used in the exergo-environmental analysis.

3. Analysis

Exergo-environmental analysis can be defined as a combination of exergy analysis and LCA. This analysis consists of three steps. The first step is exergy analysis. In this step, inlet and outlet exergy flows of each engine component should be calculated in order to determine exergy destruction of each component. The second step is an LCA of the relevant components and the overall system. The last step is the assessing environmental impact of each component exergy stream [57,58].

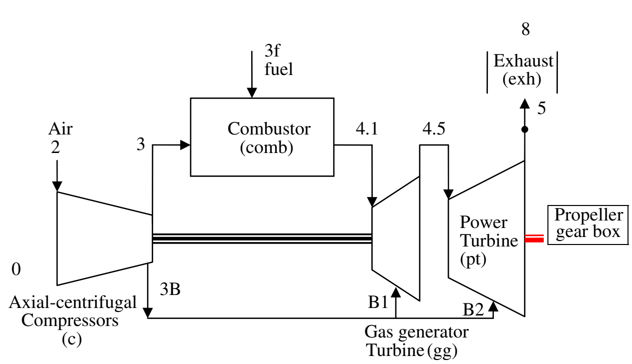


Fig. 1. Control volume of the turboprop engine.

Table 1
Turboprop engine parameters at ground operation.

Parameter	Value
Atmospheric pressure (kPa)	93
Atmospheric temperature (K)	279
Humidity (%)	22.77
Power turbine inlet temperature (K)	1109
Power turbine speed (RPM)	22,011
Gas generator speed (RPM)	42,523
Engine air flow (kg s^{-1})	4.73
Fuel (Jet-A1) heating value (kJ kg^{-1})	43,400
Fuel mass flow (kg s^{-1})	0.1

Source: [31].

3.1. Exergy analysis

Numerous ways of formulating energy and exergy for various energy systems are given in detail elsewhere. It is very useful to define performance parameters based on energy and exergy. Some of the parameters are obtained from engine ground test run. Since not all parameters are measured during testing, the remaining parameters have been calculated by parametrical cycle analysis. After obtaining all the temperature, pressure and flow mass values at each station the energy and exergy values have been calculated in the inlet and exit of engine components by using Table 2. More importantly, turboprop engine has been run at maximum power condition (for maximum power setting, engine torque value was observed as 630 N m). Majority of the engine parameters are obtained from engine test ground run. Remaining few parameters has been calculated parametrically. The energy and exergy equations for the turboprop engine are shown in Table 3. Implementation to exergetic equations to the engine components, exergy values for every location are yielded as given in Table 4.

3.2. Exergo-economic analysis

Exergo-economic analysis is a unique combination of exergy analysis and cost analysis conducted at the component level, to provide the designer or operator of an energy conversion system with information crucial to the design of a cost-effective system. This information cannot be supplied through energy, exergy, and cost analyses conducted separately [34]. In exergo-economic analysis, cost of each exergy stream is determined. Inlet and outlet exergy streams of the each component are associated to a monetary cost. Similar to this, environmental cost of each exergy stream of the engine components is determined in exergo-environmental analysis [59]. Exergo-economic aspect of the turboprop engine used in this study was analyzed by Aydin et al. [31]. Some Exergo-economic parameters are listed in Table 5. The purchased equipment cost (PEC) of the main engine components have been obtained by adding the average cost of all other engine equipment costs such as accessories, frames and gearbox. The component costs are approximately estimated ones and not

Table 2
Turboprop engine thermodynamic values.

Station	Station name	Mass flow (kg s^{-1})	Temperature (K)	Pressure (kPa)
0	Air	4.73	279	93
2	Compressor inlet	4.73	279	92
3B, B1, B2	Cooling air	0.355	700	1600
3	Combustor inlet	4.35	725	1638
3f	Fuel	0.1	279	3500
4.1	Combustor exit	4.45	1547	1580
4.5	Power turbine inlet	4.76	1109	332
5	Power turbine exit	4.81	847	98

Source: [31].

Table 3
Energy and exergy balance equations of the turboprop engine.

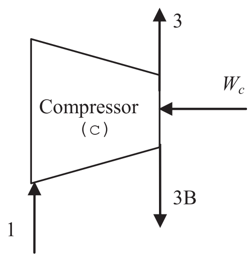
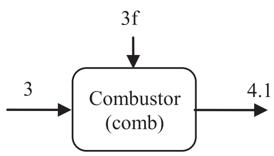
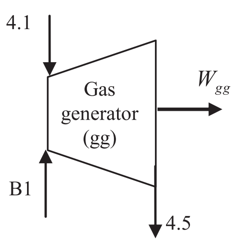
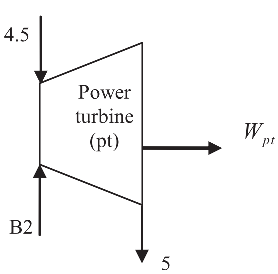
Control volume	Energy and exergy balance equations
	$\dot{E}_1+\dot{W}_c-\dot{E}_3-\dot{E}_{3B} = 0\dot{E}_1+\dot{W}_c-\dot{E}_3 -\dot{E}_{3B} = 0$ $\dot{W}_c+\dot{E}x_1-(\dot{E}x_3+\dot{E}x_{3B}) = \dot{E}x_{dest,c}$ $\eta_{ex,c} = \frac{\dot{E}x_3+\dot{E}x_{3B}-\dot{E}x_1}{\dot{W}_c}$
	$\dot{E}_{3f}+\dot{E}_3-\dot{E}_{4.1} = 0$ $\dot{E}x_{3f}+\dot{E}x_3-\dot{E}x_{4.1} = \dot{E}x_{dest,comb}$ $\eta_{ex,comb} = \frac{\dot{E}x_{4.1}}{\dot{E}x_f+\dot{E}x_3}$
	$\dot{E}_{4.1}+\dot{E}_{B1}-\dot{E}_{4.5}-\dot{W}_{gg} = 0$ $\dot{E}x_{4.1}+\dot{E}x_{B1}-\dot{E}x_{4.5}-\dot{W}_{gg} = \dot{E}x_{dest,gg}$ $\eta_{ex,gg} = \frac{\dot{W}_{gg}}{\dot{E}x_{4.1}-\dot{E}x_{4.5}+\dot{E}x_{B1}}$
	$\dot{E}_{4.5}+\dot{E}_{B2}-\dot{E}_5-\dot{W}_{pt} = 0$ $\dot{E}x_{4.5}+\dot{E}x_{B2}-\dot{E}x_5-\dot{W}_{pt} = \dot{E}x_{dest,pt}$ $\eta_{ex,pt} = \frac{\dot{W}_{pt}}{\dot{E}x_{4.5}-\dot{E}x_5+\dot{E}x_{B2}}$

Table 4
Results obtained from the exergy analysis.

Component stations	Exergetic value (kW)
$\dot{E}x_1$	0
$\dot{E}x_{3B}$	102
$\dot{E}x_3$	1952
$\dot{W}_C$	2450
$\dot{E}x_{dest,C}$	396
$\dot{E}x_f$	5051
$\dot{E}x_{4.1}$	5749
$\dot{E}x_{dest,comb}$	1254
$\dot{E}x_{B1}$	102
$\dot{E}x_{4.5}$	3251
$\dot{W}_{gg}$	2475
$\dot{E}x_{dest,gg}$	125
$\dot{E}x_5$	1505
$\dot{E}x_{B2}$	102
$\dot{W}_{pt}$	1561
$\dot{E}x_{dest,pt}$	172

Table 5
Exergo-economic parameters of the turboprop engine.

Item	Unit	Value
CO	US$	1,000,000
OM	US$/yr	112,000
I	%	10
J	%	12
N	yr	30
τ	h/yr	700
PR	TL/kg	1.50
ER	TL/US$	1.50
LHV	kJ/kg	43,400

indicate the exact prices. By using the parameters listed in Table 5 and exergo-economic equations, hourly levelised capital investment cost (US$/h), hourly operating and maintenance cost (US$/h) and total costs of the engine and its components have been calculated as outlined in Table 6. Results from exergo-economic analysis of the engine are shown in Table 7. In this table, exergy cost rates and unit exergy costs of the engine are summarized [31].

3.3. Life cycle assessment (LCA)

LCA is a ‘cradle-to-grave’ approach for evaluating environmental performance of energy conversion systems. Environmental impact of a product during entire life cycle (including production, operation, maintenance and disposal etc.) is considered and LCA is a useful tool to assess the environmental impact of the system [49,60].

Environmental impact assessment can be accomplished by using a quantitative indicator. In this paper, Eco-indicator 99 is selected. Eco-indicator 99 uses average European data and determines environmental impact according to three damage categories: (a) human health; (b) ecosystem quality; (c) natural resources. Final value of indicator represents combination of the damage to these categories and results are expressed as Eco-Indicator points (pts). Greater damage corresponds to a greater value of Eco-indicator points and these values are calculated by using SimaPro 7.2 software package [43,51,52].

3.4. Exergo-environmental analysis

Exergo-environmental impact rate ($\dot{B}_k$) is the expression of environmental impact metric in Eco-indicator points per unit of time (mPts/s). It is the product of specific environmental impact (mPts/GJ) and exergy rate [57]:

$$\dot{B}_k = \dot{b}_k \times \dot{E}x_k \quad (1)$$

Environmental impact rate associated with work $\dot{W}$ can be calculated as follows [57]:

$$\dot{B}_W = \dot{b}_W \times \dot{W} \quad (2)$$

Environmental impact balance for a system can be defined as environmental impact of all input streams ($\dot{B}_{in}$) plus the component

Table 6
Some economical costs of the engine components.

Component	PEC(US$)	$\dot{Z}_k^{CIC}$ (US$/h)	$\dot{Z}_k^{OM}$ (US$/h)	$\dot{Z}_k^{T}$ (US$/h)
Compressor	310,000	46.65	49.6	96.25
Combustor	125,000	18.81	20	38.81
Gas turbine	330,000	49.66	52.8	102.46
Power turbine	165,000	24.83	26.4	51.23
Exhaust	70,000	10.53	11.2	21.73
Turboprop	1,000,000	150.48	160	310.48

Source: [31].

Table 7
Exergy cost rates and unit exergy costs of the engine.

State no.	$\dot{E}x$ (GJ/h)	$\dot{C}$ (US$/h)	$\dot{c}$ (US$/GJ)
0	0	0	0
2	0	0	0
3	7.1	687	96.2
3f	16.7	421	25.2
4.1	18.6	1193	64.1
4.5	18.3	658	35.9
5	10	314	31.3
$\dot{W}_{gg}$	7.8	637	80.9
$\dot{W}_{pt}$	5	396	78.5

Source: [31].

related environmental impact ($\dot{Y}$) is equal to the sum of the environmental impacts associated with output streams ($\dot{B}_{out}$) [57]:

$$\dot{B}_{out} = \dot{B}_{in} + \dot{Y} \tag{3}$$

Component related total environmental impact of kth component can be calculated by using following equation [57]:

$$\dot{Y}_k^{TOT} = \dot{Y}_k^{CO} + \dot{Y}_k^{OM} + \dot{Y}_k^{DI} \tag{4}$$

where $\dot{Y}_k^{CO}$ and $\dot{Y}_k^{OM}$ are environmental impacts of kth component that occurs during construction phase and operation/maintenance phases, respectively. In this study, aircraft engines are assumed to be reutilized after depot level maintenance, hence environmental impact of the engine disposal $\dot{Y}_k^{DI}$ is neglected. Other component of the environmental impact metric is the environmental impact rate of exergy destruction and can be found by using following equation [57]:

$$\dot{B}_{dest} = \dot{b}_f \times \dot{E}x_{dest} \tag{5}$$

where $\dot{b}_f$ is environmental impact per unit of exergy of fuel and $\dot{E}x_{dest}$ is exergy destruction rate of relevant component. After $\dot{B}_{dest}$ is calculated, total environmental impact can be determined by summing $\dot{B}_{dest}$ and $\dot{Y}_k^{TOT}$ [57]:

$$\dot{B}_{TOT} = \dot{B}_{dest} + \dot{Y}_k^{TOT} \tag{6}$$

According to control volumes given in Fig. 1 for the engine and Table 3 for the components, auxiliary equations can be formed for each component as follows:

For the compressor (c):

$$\dot{B}_2 + \dot{B}_{W,c} + \dot{Y}_c^{TOT} = \dot{B}_3 + \dot{B}_{3B} \tag{7}$$

For the combustion chamber (comb):

$$\dot{B}_3 + \dot{B}_f + \dot{Y}_{comb}^{TOT} = \dot{B}_4 \tag{8}$$

For the gas turbine (gg):

$$\dot{B}_4 + \dot{B}_{3B} + \dot{Y}_{gg}^{TOT} = \dot{B}_{W,gg} + \dot{B}_{4.5} \tag{9}$$

For the power turbine (pt):

$$\dot{B}_{4.5} + \dot{Y}_{pt}^{TOT} = \dot{B}_{W,pt} + \dot{B}_5 \tag{10}$$

For the exhaust nozzle (exh):

$$\dot{B}_5 + \dot{Y}_{exh}^{TOT} = \dot{B}_8 \tag{11}$$

In this study, the following assumptions are taken: (a) lifetime of the engine is 30 years; (b) total annual numbers of hours year is 700 h for the engine. Furthermore, environmental impact of emission is based on following four gases: (i) carbon dioxide; (ii) oxygen; (iii) water vapour; (iv) nitrogen oxides [17].

4. Results and discussion

Exergo-environmental analysis identifies and quantifies locations, magnitudes and sources of environmental impacts of the engine components. It is based on exergy analysis and life cycle assessment. This study presents environmental analysis of the turboprop engine by using exergy at the maximum power condition given in the literature [31,34]. From an environmental point of view, exergy analysis can be taken into account as a promising tool for the aero engines. To evaluate the environmental aspects of the turboprop engine as a function of exergy, the following parameters of the turboprop engine components are taken into consideration: (a) exergetic values, (b) economical costs, (c) exergo-economic parameters, (d) economical cost rates and unit exergy costs, (e) exergo-environmental variables.

Before analysing and evaluating the results in this section, it should first be emphasized that the principal objective of this study are not to determine the exergetic performance for the turboprop engine. Rather, studying the turboprop engine at maximum power (≈1948 shp) aims how much improvement is possible for the turboprop engine for better sustainable environment.

The exergo-environmental performance of the turboprop engine with free power turbine is investigated considering measured conditions such as air and fuel mass flows, temperature and pressure for the engine components. The air conditions at the compressor inlet are observed at 93 kPa and 273 K. In our model, the humidity is fixed at 22.77%. Using cycle equations, the inlet temperature of the gas generator turbine and power turbine are calculated to be 1547 K and 1109 K, respectively. The maximum power of the turboprop engine at 630 N m torque is set at 1948 shp. We first make some another assumptions to investigate exergo-environmental aspects of the engine. These assumptions are made as follows:

- Type of fuel used is kerosene (Jet A-1) and its chemical formula is $C_{12}H_{23}$.,
- The combustion reaction is complete.,
- Compressor and turbines are assumed to be adiabatic.,

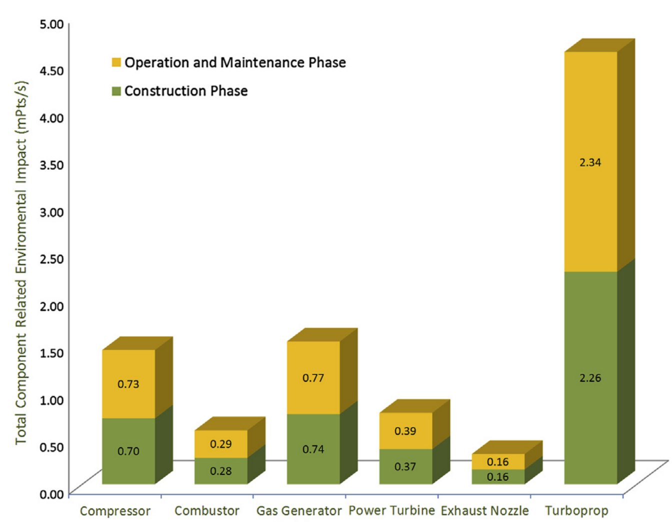


Fig. 2. Component related environmental impacts of the turboprop engine.

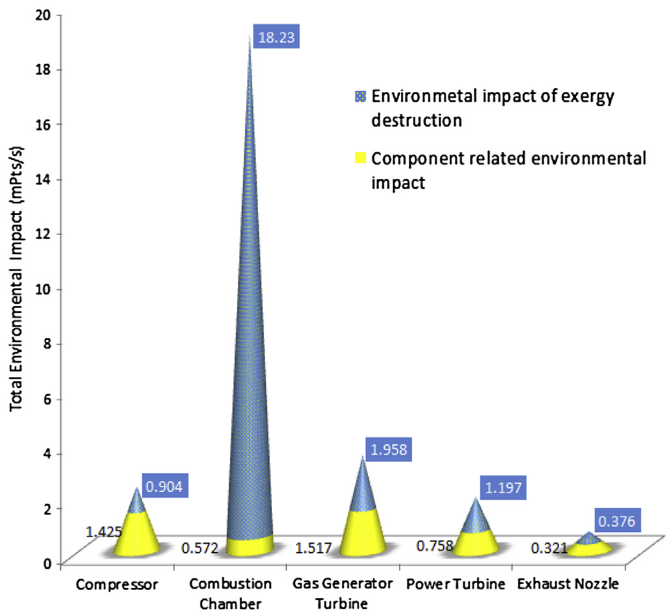


Fig. 3. Total environmental impact rates of the turboprop engine components.

- 5% of the compressor discharge air is assumed to be used as cooling and seal pressurizing purposes.
- Pumps (fuel, oil and hydraulic) and heat exchangers (fuel/air or fuel/oil) are not included in the analysis.

The main findings, which improve understanding of the exergo-environmental behaviour of the turboprop engine at maximum shaft power as follows:

- There are two parameters of environmental impact for the turboprop engine components: (a) total component related environmental impact rates; (b) environmental impact of exergy destruction. Component related environmental impact consists of two impact rates: (i) environmental impact occurs during manufacturing of engine component; (ii) environmental impact occurs during operation/maintenance of engine components. According to Fig. 2, the unit with the greatest total component related environmental impact is found at the gas generator turbine in both constructional and operation/maintenance phases with the value of 0.74 mPts/s for the constructional phase and 0.77 mPts/s for the operational/maintenance phases, respectively. On the other hand, the lowest total component related environmental impact is found to be in the exhaust nozzle (0.16 mPts/s for both constructional and operation/maintenance phases). As shown in Fig. 2, in the compressor section, total component related environmental impact value is close to the gas generator turbine. From the same figure, total component related environmental impact value for the constructional phase is calculated to be 0.37 mPts/s for the power turbine and 0.28 mPts/s for the combustor. Besides, total component related environmental impact value is calculated to be 0.39 mPts/s for the power turbine and 0.29 mPts/s for the combustor for the operation/maintenance phases.
- Component related environmental impact constitutes approximately 16.85% of total environmental impact. According to these rates, the compressor and gas turbine almost have same impact rate and can be considered first to improve in case of component related environmental impact.
- As it is shown in Fig. 2, total component related environmental impact for the turboprop engine is calculated to be 2.26 mPts/s for the constructional phase and 2.34 mPts/s for the operation and maintenance phase.
- Other parameters of the environmental impact are the environmental impact of exergy destructions. This part of the environmental impact is defined as main contributor to the overall environmental impact [23–25]. Fig. 3 shows total environmental impact rates of the engine components.
- Obtained results of exergo-environmental impact for turbofan engine are represented at Fig. 4. Analysis of represented variables expresses, that the combustion chamber is characterized by the highest rate of environmental impact (51.23%), while the

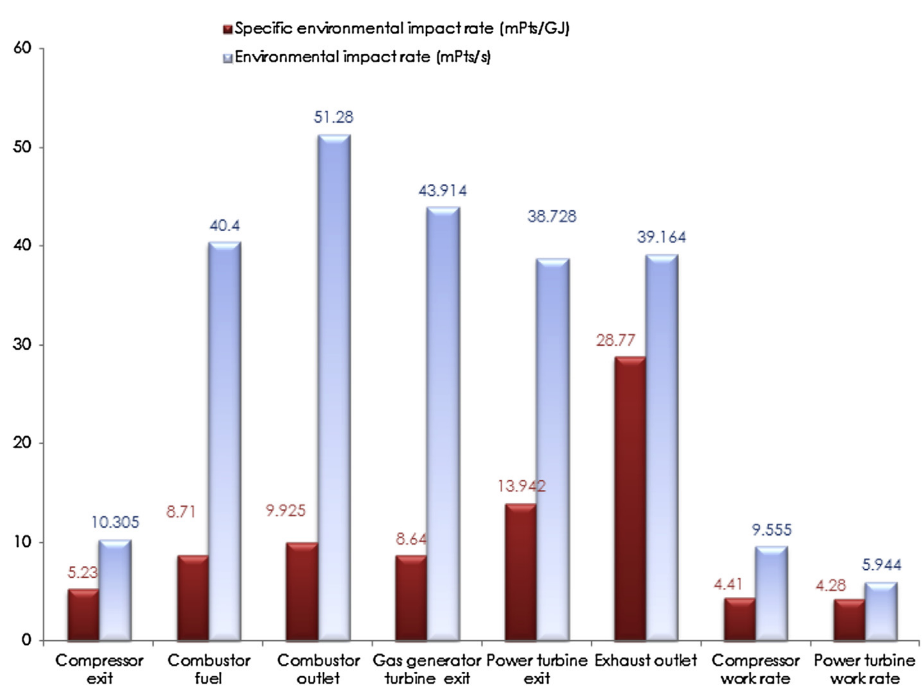


Fig. 4. Exergo-environmental variables for the engine stations.

specific environmental impact dominates at engine exhaust outlet.

- According to exergetic results, the biggest candidate for improving is the combustion chamber. This component creates 68.98% of the overall environmental impact while 96.8% of this impact is associated with exergy destruction. These results are very parallel to literature [31,34,35]. In these studies, it is reported that highest exergy destruction occurs in combustion chamber due to irreversibilities result from combustion process.
- As stated previously, there is no study on exergo-environmental analysis of aircraft engines and there is no chance to compare result of this paper to similar ones. So, exergo-environmental analysis of stationary gas turbine power plants which have similar components as aircraft engines are examined. Results of our study indicate that the combustion chamber, where the chemical reaction occurs, causes the largest portion of total environmental impact of a turboprop aircraft engine.

4. Conclusions

To develop approaches that effectively reduce engine environmental effect of aircraft, it is necessary to understand the mechanisms that have enabled improvements in thermodynamic efficiency of aircraft propulsion systems. In the present paper, exergo-environmental method is applied for the first time to an aircraft turboprop engine. This study has presented environmental aspects for a turboprop engine commonly used in regional transportation as well.

Approximately 17% of total environmental impact of turboprop engine is result of component related environmental impact and remaining part is result of exergy destructions of the turboprop engine components. Compressor, combustion chamber, gas generator turbine, power turbine and exhaust nozzle create 9%, 69%, 13%, 7%, 2% of total environmental impact of the engine, respectively.

Results have indicated that combustion chamber has the highest priority for improvement. Beside conventional analysis, advanced exergo-environmental analysis which is considered as a valuable supplement to conventional analysis can be applied to get more accurate results by defining avoidable and unavoidable parts of environmental impacts

Researchers and scientists are working hard to minimize anthropogenic degradation of the environment. One solution is alternative energy sources to fossil fuels like biofuels or hybrid electric propulsion systems. However in short and medium term, feasible application of these alternative energy sources to the aircraft power plants seems unrealistic, and that means dependence to the fossil fuel appears to be inevitable. The development of exergo-environmental analysis for aircraft propulsion systems can play a significant role in the investigation of the possibilities and advantages of green regional aircraft. Hence, approaches like exergy-based analysis that contribute to improve environmental effects of aircraft engines can offer best solutions.

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Nomenclature

AB	afterburner
$\dot{b}$	specific environmental impact rate (mPts/GJ)
$\dot{B}$	environmental impact rate (mPts/s)
BPR	bypass ratio
$\dot{C}$	cost rate of exergy stream
CHP	combined heat and power
CT7-9C	model of the turboprop aircraft engine
$\dot{E}R$	exchange rate
$\dot{E}x$	exergy rate (kW)
GHG	greenhouse gases
I	interest rate
j	salvage rate
k	kth component
km	kilometers
kph	kilometers per hour
LCA	life cycle assessment
LHV	lower heating value (kJ/kg)
LTO	landing and take-off
mph	miles per hour
N	engine lifetime
p	pressure
PR	fuel price
PEC	purchased equipment cost
pts	eco-indicator points
shp	shaft horsepower
SOFC	solid oxide fuel cell
T	the total number of hours of the engine
τ	temperature
$\dot{W}$	work (kW)
$\dot{Y}$	component related environmental impact (mPts/s)
$\dot{Z}$	capital cost flow

Superscripts and subscripts

c	compressor
comb	combustion chamber
CO	construction
dest	destruction
DI	disposal
exh	exhaust nozzle
f	fuel
gg	gas turbine
in	input
k	kth component
OM	operation and maintenance
out	output
pt	power turbine
TOT	total
w	work
0	dead state (environment) conditions
0,1,2, …, B1	station numbering of the engine

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