Chapter 42
Exergo-Economic Analysis of an Experimental Aircraft Turboprop Engine Under Low Torque Condition

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Abstract Exergo-economic analysis is an unique combination of exergy analysis and cost analysis conducted at the component level. 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. This is essential to detect cost-ineffective processes and identify technical options which could improve the cost effectiveness of the overall energy system. In this study, exergo-economic analysis is applied to an aircraft turboprop engine. Analysis is based on experimental values at low torque condition (240 N m). Main components of investigated turboprop engine are the compressor, the combustor, the gas generator turbine, the free power turbine and the exhaust. Cost balance equations have been formed for all components individually and exergo-economic parameters including cost rates and unit exergy costs have been calculated for each component.

42.1 Introduction

Energy analysis (also known as first law analysis) states conservation of energy, and that is not enough for identifying the real inefficiencies and imperfections. It is a measure of quantity of energy only. First law based analysis can be misleading alone. Besides, exergy analysis (also known as second law analysis) complements

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energy analysis and, identifies and quantifies locations, magnitudes and sources of irreversibilities through exergy destruction rates of each engine component. This combination gives a chance to designers and operators to use non-renewable resources, such as kerosene ($C_{12}H_{23}$) which is used in aircraft engines as fuel, effectively and also to reduce operating costs besides environmental impacts [1, 2]. Exergy analysis is a measure of both quantity and quality of energy. Exergo-economic analysis is an unique combination of exergy analysis and cost analysis conducted at the component level. 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.

Exergo-economic analysis is widely used to evaluate cost efficiency of energy conversion systems, but application of these analyses to the aircraft engines are only performed on some studies [3–6]. In this study, exergo-economic analysis is applied to an experimental aircraft turboprop engine that operates under 240 N m torque condition.

42.2 System Description

Turboprop engines are well-known with their low fuel consumption especially in short-haul flights (under 1,000 miles) [7] and have the highest propulsive efficiency at flight speeds of 400 mph ($\cong 650$ kph) compared to turbojet and turbofan engines [8]. A study showed that an advanced turboprop aircraft concept cruising at between 640 and 700 kph will result 25 % cut of CO_2 emissions by reducing fuel consumption [9].

Turboprop engines use a gas turbine core to drive an external propeller which produces higher bypass ratios (BPR) nearly the same as turbofan engines. This higher BPR can be an explanation of how turboprop engines have high fuel efficiency. Because, higher BPR means smaller amount of air flow burned inside the engine core and that makes possible for turboprops to generate a lot of thrust at low fuel consumption [10].

The external propeller of turboprop engine should rotate at very low speed in comparison with its driving turbine; therefore a gear box is used in turboprop engines to provide a speed reduction of almost 1:15. This reduction is necessary, because no propeller can resist stresses and forces occur as a consequence of centrifugal forces when it rotates at the same speed of turbine. Moreover, at high subsonic flights (over 0.7 Mach) the tips of blades can approach supersonic speeds, flow separates and shock waves form. This causes to decreased propeller efficiency and poor overall engine performance, hence turboprops give best performance at subsonic flights (under 650 kph) [8].

In this study, a turboprop aircraft engine (CT7-9C) is investigated. This engine is commercial turboprop version of GE T700 turboshaft engine. CT7-9 has been operated in several aircrafts since 1984, and more than 1,500 engine have been

produced. Over 30 million flight hours are logged for this engine all around the World [11].

Main components of CT7-9C are compressor (consist of five axial stages and one centrifugal impeller stage), combustion chamber (annular type), gas turbine (two axial stages), power turbine (two axial stages) and an exhaust nozzle. Control volume of this engine is shown in Fig. 42.1 [1]. Components of the engine and two shafts can be seen in this schematic. CT7-9C turboprop engine has free turbine which means the propeller is driven by a designated turbine named power turbine. Another turbine named gas turbine drives compressor, and thus engine start mechanism does not requires rotating the propeller and accessory gearbox. It only drives compressor and gas turbine and this provides to reduce torque loads [12].

42.3 Methodology and Analysis

Exergy analysis provides to assess sources, locations and true magnitudes of exergy destructions. As stated before, exergy analysis complements first law based energy analysis and combines first law analysis and second law analysis together. Exergy can be divided into four parts: physical exergy, chemical exergy, potential exergy and kinetic exergy. Potential and kinetic exergies are neglected in this study. Physical exergy and chemical exergy (only for combustion chamber) are taken into account in calculations [13].

42.3.1 Assumptions

- Exergy is defined as energy that is out of equilibrium with the reference environment [14]. Hence, determining properties of the term environment accurately is one of the key issues such exergy based analysis. In this study, temperature and pressure of the environment (T_0 and p_0) are taken as 279 K and 93 kPa, respectively.
- CT7-9C turboprop engine lifetime of 30 years and 700 total annual numbers of hours of engine at full load per year is assumed,
- $\dot{C}_{W_{comp}} = \dot{C}_{W_{ggt}}$,
- $\dot{C}_4 = \dot{C}_{45} = \dot{C}_5$,
- All system units are assumed to be adiabatic,
- Air and exhaust gases in the engine are ideal gases,
- The combustion reaction is complete,
- 5 % of the compressor discharge air is assumed to be used as cooling and seal pressurising purposes,
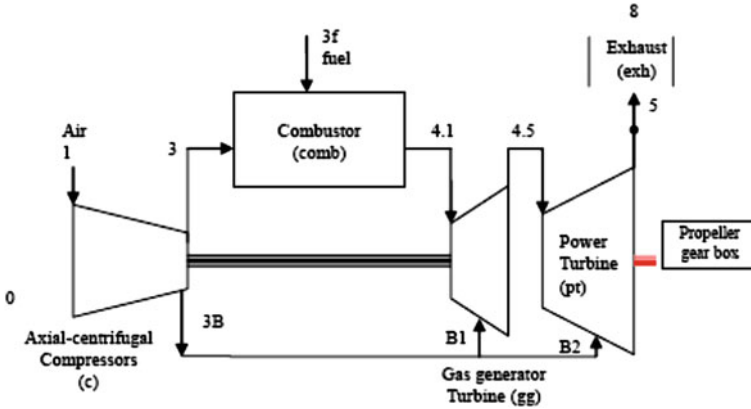
Fig. 42.1 Control volume of turboprop engine [1]

- Pumps (fuel, oil and hydraulic) and heat exchangers (fuel = air or fuel = oil) are not included in the analysis,
- The kinetic and potential exergies are neglected,
- Chemical exergy is neglected other than combustion chamber [3].

42.3.2 Exergo-Economic Equations

Main equations for exergo-economic analysis can be written as follows [3]:

$$\sum_{in} \dot{C}_k + \dot{Z}_k^{TOT} = \sum_{in} \dot{C}_k + \dot{C}_w \tag{42.1}$$

$$\dot{C}_k = c\dot{E}x_k \tag{42.2}$$

$$\dot{C}_w = c\dot{W} \tag{42.3}$$

$$\dot{Z}_k^{TOT} = \dot{Z}_k^{CIC} + \dot{Z}_k^{OM} \tag{42.4}$$

where $\dot{C}_k$ and $\dot{C}_w$ are the exergy costs of the flow of kth component and power; c is the unit exergy costs of stream and power; $\dot{E}x_k$ and $\dot{W}$are the exergy of stream and power entering and leaving related the control volume; $\dot{Z}_k^{CIC}$, $\dot{Z}_k^{OM}$ and $\dot{Z}_k^{TOT}$ are hourly levelised costs of capital investment cost, operating and maintenance and the total levelised cost of equipment inside the control volume, respectively.

Table 42.1 Matrix system for linear equation system

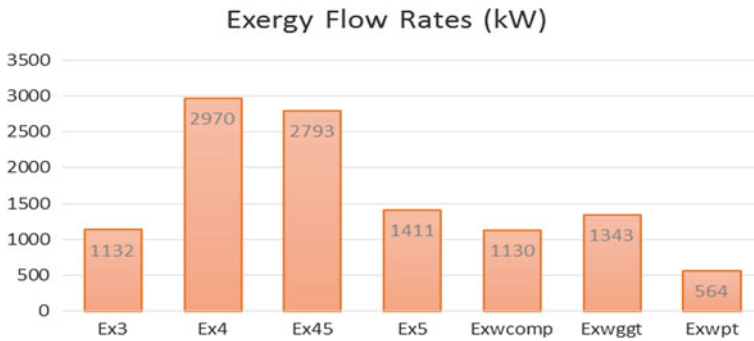| c_3	c_4	$c_{w_{gt}}$	$c_{w_{pt}}$	const.
−4.075	0	4.068	0	−96.25
4.075	−10.692	0	0	−459.81
0	0.637	−4.835	0	−102.46
0	4.975	0	−2.030	−51.23

Fig. 42.2 Exergy flow rates

42.3.3 Cost Balance Equations

Cost balance equations are formed by using main equations and control volume of the engine, and are given below in (42.5) (42.6) (42.7) (42.8) and (42.9) for the compressor, combustion chamber, gas generator turbine, power turbine and exhaust nozzle, respectively:

$$\dot{C}_1 + \dot{C}w_{comp} + \dot{Z}_{comp}^{TOT} = \dot{C}_3 + \dot{C}_B \tag{42.5}$$

$$\dot{C}_3 + \dot{C}_f + \dot{Z}_{cc}^{TOT} = \dot{C}_4 \tag{42.6}$$

$$\dot{C}_4 + \dot{Z}_{ggt}^{TOT} = \dot{C}_{w_{ggt}} + \dot{C}_{45} \tag{42.7}$$

$$\dot{C}_{45} + \dot{C}_B + \dot{Z}_{ppt}^{TOT} = \dot{C}_{w_{pt}} + \dot{C}_5 \tag{42.8}$$

$$\dot{C}_5 + \dot{Z}_{ex}^{TOT} = +\dot{C}_8 \tag{42.9}$$

After cost balance equations above are formed, a linear equation system is obtained with 5 equations and 8 variables. This equation system can be solved with the aid of a matrix system which is given in Table 42.1.

Table 42.2 Exergy cost rates and unit exergy cost rates

Station number	$\dot{c}$ ($/Gj)	$\dot{C}$ ($/h)
3	53.1	216.4
4	63.2	676.2
45	63.2	635.9
5	63.2	321.2
w_{comp}	29.5	120.1
w_{ggt}	29.5	142.7
w_{pt}	180.2	365.9

42.4 Results and Discussions

There are roughly two main outputs for the exergo-economic analysis: Exergy cost rates ($\dot{C}$) and unit exergy costs ($\dot{c}$). Matrix system is solved and unit exergy cost rates are found. As stated before in (42.2) and (42.3), exergy cost rate ($\dot{C}$) is the product of unit exergy cost rate ($\dot{c}$) and exergy flow rate ($\dot{Ex}$). Exergy flow rates of turboprop engine stations are given in Fig. 42.2. Final results of exergo-economic analysis are shown in Table 42.2.

42.5 Conclusion

In this paper, exergo-economic analysis of an aircraft turboprop engine is performed. Cost performance of engine components are investigated individually. Power turbine produces shaft horse power to drive propeller, and exergy cost rates and unit exergy cost rates for power turbine of the engine is calculated as 365,9$/h and 180,2$/Gj respectively. The highest value for exergy cost rate is found for inlet stream of gas generator turbine (station number 4) with the value of 676.2$/h, while the highest unit exergy cost value is found for power turbine with the value of 180.2$/Gj. These results can help to operators and designers to identify cost-ineffective processes and identify technical options which could improve the cost effectiveness of the overall turboprop engine and engine components.

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