INTERNATIONAL JOURNAL OF AERONAUTICS AND ASTRONAUTICS
IJAA
2021, Vol. No: 2(1), 14-17

Research Article

Thermodynamic analysis of a small-scale gas turbine jet engine

Soner Şen*

Department of Airplane Airframe and Engine Maintenance, School of Civil Aviation, Selçuk University, 42250 Konya, Turkey

ARTICLE INFO

* Corresponding author
sensoner@selcuk.edu.tr

Received March 15, 2021
Revised April 26, 2021
Accepted April 26, 2021

Soner Şen
0000-0003-3385-5577

ABSTRACT

Gas turbine aircraft engines are the most commonly used engine type in today's aircrafts. Turbojet engine, which is one of the gas turbine engine type, is used especially in warplanes and some passenger planes with its high power generation and speed. In this study, the thermodynamic analysis of a small-scale jet engine that generates thrust with reaction from gas turbine engine is carried out with the data obtained under real operating conditions. With the analysis, exergy destructions, exergy efficiency, exergy improvement potential and relative exergy destroying rate of small-scale jet engine parts were calculated. According to the results obtained, it was seen that the greatest exergy destruction was in the combustion chamber, so at first, the exergy improvement should be done in the combustion chamber.

Keywords: Jet Engine; Thermodynamic Analysis; Gas Turbine; Exergy; Aircraft

1. Introduction

Aircrafts are the most important civil transportation vehicles of today, and they are also the military power element of countries. Aircraft with a wide variety of structures are equipped with power sources that create their own propulsion in line with their intended use. Some of these engines are ramjet, scramjet, turboramjet, turbojet, turboprop, turbofan and turboshaft. There are engine types specific to the flight conditions of the aircraft in which they are used. Turbojet engines, which will be especially emphasized in the study, are the type of aircraft engine that allows sudden altitude changes that can provide thrust for high speed flight conditions (such as Mach 4.0). These engines have been and continue to be used in intercontinental passenger aircraft such as the Concorde in civil aviation and fighter aircraft such as the F-16 in military aviation.

The first law of thermodynamics is on the conservation of energy. That is, it deals with the transformations of energy. The energy efficiency of the system can be determined in an analysis to be made by applying the first law of thermodynamics. The second law of thermodynamics enables the analysis of the quality of energy. This reveals the irreversibilities and the potential for improvement in the system [1].

Exergy is defined as the useful part of energy, that is, the highest theoretical work that can be taken from the system [2]. Performing a thermodynamic analysis based on exergy analysis can reveal which parts of the system have the greatest energy losses. This shows the potential for improvement in those parts.

Although thermodynamic analyzes have been made according to design information for various engine types in the literature [3-8], a thermodynamic analysis has been made that based on real experimental measurements of the Jetcat P-160 Rxi-B model aircraft jet engine, which has a simpler structure in order to be more realistic. Thus, the thermodynamic efficiency of this simpler and more inefficient model aircraft engines is emphasized.

2. Thermodynamically Analyzed System

One of the forces affecting an airplane is the propulsion force, and this thrust can be provided by a wide variety of engine structures. Gas turbine engine structures are generally used in aircraft used in today's conditions. The type of engine to be thermodynamically analyzed is a small-scale turbojet aircraft engine operating according to the gas turbine theory. Turbojet engines operate according to the Brayton cycle, which forms the basis of the gas turbine engine.

In a turbojet engine operating according to the Brayton cycle, there are air intake housing, compressor, combustion chamber, turbine and nozzle that form the thrust with the exhaust gases are been constitute the engine parts. According to this cycle, the air is first taken to the compressor with the help of the air intake, where the temperature rises together with the pressure. Then, the compressed air is sent to the combustion chamber, fuel is sprayed and combustion is realized and the energy of the fluid is increased. The high temperature work gases coming out of the combustion chamber turn the turbine and the shaft work required for the compressor is obtained. The high-energy work gases from the turbine are thrown from the exhaust nozzle at high speed and jet propulsion is provided. Technical characteristics of the mini jet engine used in the calculations are given in Table 1. During the experiments with this engine, the temperature and pressure values of the parts allocated to the stations were measured.

Table 1. Technical characteristics of the jet engine that used in calculations

Jet Engine Specifications	
Design Max Thrust:	160 N @123,000 rpm
Compression ratio:	3.1 / 1
Specific fuel consumption:	520 ml/ min @max rpm
Compressor type:	Single stage radial
Turbine type:	Single stage axial
Engine Weight:	1530g
Diameter:	112mm
Length:	285mm
RPM Range:	33,000 (idle) - 123,000 (max)

3. Mathematical Formulation

The energy analysis of a system to be thermodynamically analyzed is based on the principle of conservation of energy. The turbojet engine, which is a gas turbine engine, is also an example of a continuous flow open system and its analysis is done according to this principle. For this reason, the mass and energy balance in and out should be written first [9].

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

$$\sum \dot{E}_{in} = \sum \dot{E}_{out} \quad (2)$$

As can be seen from these equations, the mass and energies entering and leaving the system are equal to each other and there is no mass and energy absorbed in the system. Components that make up exergy are kinetic, potential, physical and chemical exergy [10]. If the kinetic and potential energy changes of the work fluid are neglected in the turbojet engine structure, the exergy components appear physically and chemically. Physical exergy expression can be written as below [11].

$$\dot{E}x_{phs} = \dot{m}\left[(h-h_0)-T_0(s-s_0)\right] \quad (3)$$

In a system operating according to the Brayton cycle, the work fluid is air and gases that are the end products of combustion. According to the ideal gas acceptance, physical exergy can be written as follows [11].

$$\dot{E}x_{phs} = \dot{m}\left[C_p(T-T_0)-T_0\left(C_p \ln\left(\frac{T}{T_0}\right)-R\ln\left(\frac{P}{P_0}\right)\right)\right] \quad (4)$$

In the equation given above, specific heat values for the work fluid air and exhaust gases can be calculated as follows [12].

$$C_{p,air} = 1.04841-(383.719/10^6)T+(9.45387/10^7)T^2 -(5.49031/10^{10})T^3+(7.92981/10^{14})T^4 \quad (5)$$

$$C_{p,exh} = \left(\sum N_i M_i C_{p,i}\right)/\left(\sum N_i M_i\right) \quad (6)$$

They are kerosene-based fuels containing C, H, O, S components in jet fuels. For a fuel with the general formula $C_xH_yO_zS_w$ and its chemical exergies for the end-of-combustion gases, if the calorific value of the fuel is expressed as H_{und}, it can be calculated as follows respectively [13].

$$\dot{E}x_{che,fuel} = \dot{m}_{fuel}H_{und}\begin{bmatrix}1.0401+0.01728(y/z)\\ +0.0432(z/x)+\\ 0.2196(w/x)(1-2.0628(y/x))\end{bmatrix} \quad (7)$$

$$\dot{E}x_{che,exh} = (\dot{m}_{exh}/M_{exh})\left[\sum x_i ex_{che,i} + RT_0\sum x_i \ln x_i\right] \quad (8)$$

In Equation 8, x_i denotes the molar ratio of the combustion gas component, and M_{exh} the molar weight. According to the Fuel-Product rule defined in the literature; the quantities desired to be obtained from a thermodynamic system are defined as the product, and the quantities given to the system for this purpose are defined as fuel. In this direction, exergy destruction in the system can be expressed as follows [13].

$$\dot{E}x_{destroy} = \dot{E}x_{fuel} - \dot{E}x_{product} - \dot{E}x_{lost} \quad (9)$$

According to this equation, exergy destruction occurring in a system is obtained by subtracting the exergy products of the products entering the system and the lost exergy in the system. In this equation, all data entering the system are expressed as fuel. In addition, all of the heat, work and fluids that pass through the system boundaries are also called products. Exergy losses also indicate exergy destructions that cannot be prevented, no matter what adjustments are made in the system. The energy and exergy efficiency of an engine operating according to the thermodynamic cycle is the ratio of the energy and exergy value of the products defined for the system to the energy and exergy value of the fuel used [13].

$$\eta = \dot{E}_{products} - \dot{E}_{fuel} \quad (10)$$

$$\eta_{Ex} = \dot{E}x_{products} - \dot{E}x_{fuel} = 1 - \left[\left(\dot{E}x_{destroy} + \dot{E}x_{lost}\right) / \dot{E}x_{fuel}\right] \quad (11)$$

If we know how much irreversibilities are reduced in a system, we can get the higher efficiency of the system. This is also valid for the turbojet engine we analyzed. Accordingly, the exergy improvement potential of the turbojet engine can be expressed in the following equation given by Van Gool [14].

$$I\dot{P}_{ex} = (1 - \eta_{ex})\dot{E}x_{destroy} \quad (12)$$

In the system to be analyzed, the relative exergy destruction rate is obtained by proportioning the exergy destruction occurring in any motor part of the entire motor system [15]. This shows us in which part of the system of the exergy destruction is high.

$$x_i = \dot{E}x_{destroy,i} / \dot{E}x_{destroy} \quad (13)$$

4. Thermodynamic Analysis

Before the thermodynamic analysis of the Mini Jet engine, the engine was divided into stations and the entry and exit points of each station were numbered. Accordingly, the inlet of the air from the air intake is numbered as 0 and the compressor inlet and outlet is 1 and 2, the combustion chamber inlet and outlet is 2 and 3, and the turbine inlet and outlet are numbered as 3 and 4. In addition, 2.1 number has been given for fuel intake. Thus, the compressor air from station 2 and fuel from station 2.1 entered the combustion chamber. The schematic representation based on this regional separation is given in Figure 1 and the view of the experimental set is given in Figure 2.

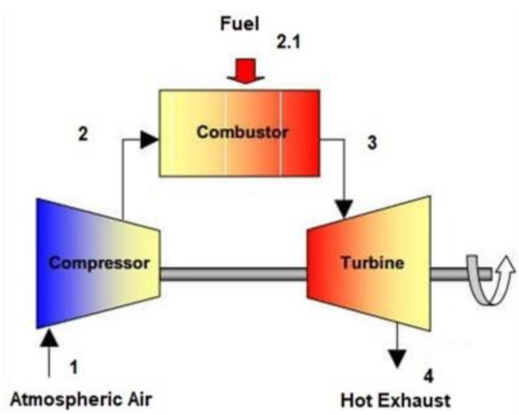

Fig. 1. Schematic diagram of the numbered zones

The temperature and pressure values of each numbered stations of the engine, which thermodynamic analysis was made, were obtained in the experimental study with Jet-A fuel and are presented in Table 2.

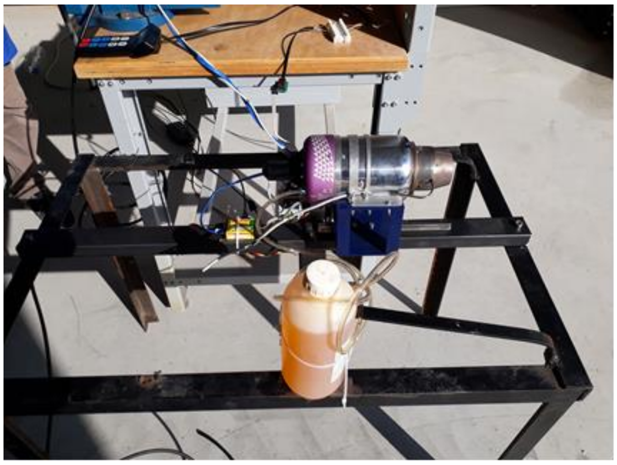

Fig. 2. The view of the small-scale turbojet engine experimental setup

Table 2. Thermodynamic cycle values of the gas turbine jet engine

Numbered station	Fluid Type	P (kPa)	T (K)	Mass flow (kg/s)
0	Air	99.411	293.150	0.32500
1	Air	99.411	298.150	0.32500
2	Air	300.178	328.441	0.32500
2.1	Fuel	99.411	298.150	0.00625
3	Comb. gas	291.478	973.42	0.33125
4	Comb. gas	157.145	845.450	0.33125

With these given data, various assumptions must be made in order to perform thermodynamic analysis. These assumptions are as follows.

- The system is a continuous flow and open system.
- Air and burnt gases, which are work fluids, are considered as ideal gases.
- It is assumed that the fuel burns completely in the combustion chamber.
- Compressor and turbine adiabatic efficiencies can be accepted as 100%.
- Kinetic and potential energy and exergy changes can be neglected.

In addition, the environment in which the engine is operated has been evaluated as a dead environment in the exergy analysis. As a result of this assumptions and experimental measurement data, the results obtained by performing the exergy analysis of the Jetcat P160 Rx-i jet engine are presented in Table 3.

Table 3. Thermodynamic analysis results of the Jetcat P160 Rx-i turbojet engine

Part of the Jet Engine	$\dot{E}x_{destroy,i}$ (kW)	η_{Ex} (%)	$I\dot{P}_{ex}$ (kW)	x_i
Compressor	2.821	88.145	0.334	0.019
Comb. chamber	141.082	74.568	35.879	0.961
Turbine	2.754	92.011	0.220	0.018

When the table is examined, it is seen that the highest exergy destruction is in the combustion chamber. This is followed by the compressor and the turbine, respectively. Another data explaining this situation is the combustion chamber with the lowest exergy efficiency and the exergy efficiency here is 74.568%. In the combustion chamber where irreversibility is highest, the exergy efficiency is also the lowest. In this case, the combustion chamber with 35.879 kW is the highest potential of curability. In this case, improvements must start from the combustion chamber. This is followed by the compressor with 0.334 kW and the turbine with 0.220 kW, respectively. Figure 3 shows the ratio of the exergy destruction of each part of the jet engine to the total exergy destruction. As can be seen from here, the greatest exergy destruction belongs to the combustion chamber with 96.185%.

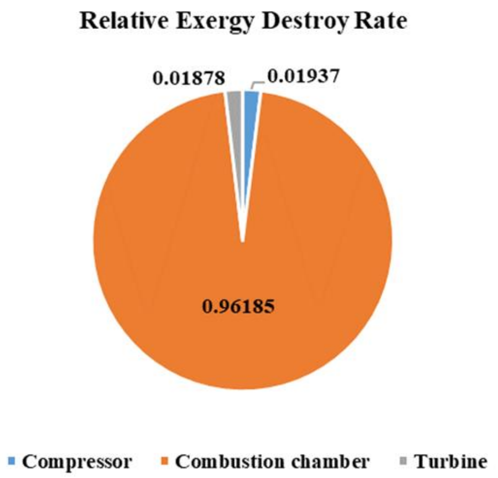

Fig. 3. Relative exergy destroy rate of the engine parts

5. Conclusion

In this study, thermodynamic analysis of a mini jet engine under real operating conditions has been made. As a result of this study, the following data were obtained;

- In the past, thermodynamic analysis made under various assumptions for engines in the literature. But this study thermodynamic analysis was applied on a real jet engine and thus the results were obtained more realistic.
- According to the results, it was seen that the exergy improvement should be done in the combustion chamber first, since the greatest exergy destruction is in the combustion chamber.
- The data obtained showed that the combustion chamber design should be emphasized first in the different versions of the engine considered.
- The magnitude of exergy destruction was followed by the compressor and the turbine, respectively. Improvements should also be made in the compressor and turbine after the combustion chamber.

Acknowledgment
The author acknowledge the financial support provided by Muson Makine San. ve Tic. Ltd. Şti. and thanks to Selçuk University for their support.

References

[1] Dincer, I., Rosen, M.A., Exergy: energy, environment and sustainable development, Elsevier, 2012.
[2] Tsatsaronis, G., 2007. Definitions and nomenclature in exergy analysis and exergoeconomics, *Energy*, 32, 249-253.
[3] Turgut, E.T., Karakoc, T.H., Hepbasli, A., 2009. Exergoeconomic analysis of an aircraft turbofan engine, *International Journal of Exergy*, 6, 277-294.
[4] Aydin, H., Turan, O., Midilli, A., Karakoc, T.H., 2012. Exergetic and exergo-economic analysis of a turboprop engine: a case study for CT7-9C, *International Journal of Exergy*, 11, 69-88.
[5] Aydin, H., Turan, O., Midilli, A., Karakoc, T.H., 2013. Energetic and exergetic performance assessment of a turboprop engine at various loads, *International Journal of Exergy*,13,543-564.
[6] Balli, O., Hepbasli, A., 2013. Exergoeconomic, sustainability and environmental damage cost analyses of T56 turboprop engine, *Energy*, 64, 582-600.
[7] Tona, C., Antonio, P., Pellegrini, L.F., de Oliveira, Jr. S., 2010. Exergy and thermoeconomic analysis of a turbofan engine during a typical commercial flight, *Energy*, 35, 952-959.
[8] Tai, V.C., See, P.C., Mares, C., 2014. Optimisation of energy and exergy of turbofan engines using genetic algorithms, *International Journal of Sustainable Aviation*, 1, 25-42.
[9] Moran, M.J., Shapiro, H.N., Boettner, D.D., Bailey, M.B., Fundamentals of engineering thermodynamics, *John Wiley & Sons Inc*, 2011.
[10] Romero, J. C., Linares, P., 2014. Exergy as a global energy sustainability indicator: a review of the state of the art, *Renewable and Sustainable Energy Reviews*, 33, 427-442.
[11] Kotas, T.J., The exergy method of thermal plant analysis, *Exergon Publishing Company UK Ltd., London*, 2012.
[12] Heywood, J.B., Internal combustion engine fundamentals, *McGraw-Hill*, 1988.
[13] Tsatsaronis, G., 1993. Thermoeconomic analysis and optimization of energy systems, *Progress in Energy and Combustion Systems*, 19, 227-257.
[14] Van Gool, W., 1992. Exergy analysis of industrial processes, *Energy*, 17, 791-803.
[15] Xiang, J.Y., Cali, M. and Santarelli, M., 2004. Calculation for physical and chemical exergy of flows in systems elaborating mixed-phase flows and a case study in an IRSOFC plant, *International Journal of Energy Research*, 28, 101-115.