DE GRUYTER Int J Turbo Jet Eng 2017; 34(2): 177–186

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Thrust Performance Evaluation of a Turbofan Engine Based on Exergetic Approach and Thrust Management in Aircraft

DOI 10.1515/tjj-2015-0065
Received November 30, 2015; accepted December 22, 2015

Abstract: The environmental parameters such as temperature and air pressure which are changing depending on altitudes are effective on thrust and fuel consumption of aircraft engines. In flights with long routes, thrust management function in airplane information system has a structure that ensures altitude and performance management. This study focused on thrust changes throughout all flight were examined by taking into consideration their energy and exergy performances for fuel consumption of an aircraft engine used in flight with long route were taken as reference. The energetic and exergetic performance evaluations were made under the various altitude conditions. The thrust changes for different altitude conditions were obtained to be at 86.53 % in descending direction and at 142.58 % in ascending direction while the energy and exergy efficiency changes for the referenced engine were found to be at 80.77 % and 84.45 %, respectively. The results revealed here can be helpful to manage thrust and reduce fuel consumption, but engine performance will be in accordance with operation requirements.

Keywords: energy, exergy, gas turbine, thrust, thermodynamics, turbofan

PACS® (2010). 05.70.Ln – Nonequilibrium and irreversible thermodynamics / 88.05.Bc – Energy efficiency, definitions and standards

Introduction

Atmospheric conditions have direct effect on aircraft engine performances in three ways: drive, fuel and thrust. In both passengers and cargo transportations, aircraft management based on flight altitude is a matter dealt with current flight information system. Thrust control or thrust management is one of the most important factors of these environmental parameters. Thrust and thrust management in aircraft are a process that directly affects all engine parameters throughout all flight process, particularly in terms of flight safety. Indeed, thrust management has an important function that manages relationship between the aircraft altitude and power within the information control management system of aircraft and this function is monitored continuously by the pilot. For instance, unexpected increases in exhaust temperate are undesired. In this case, pilot immediately reduces thrust and indirectly reduces the altitude. In addition to such driving effects, it should be seen as a control tool with respect to its effects on engine performance and environmental emission [1]. This and similar cases in dynamic flight process affect directly thrust control parameters, which are usually evaluated with aerodynamic data. The basic source of aerodynamic parameters like speed, weight and momentum is cycle stages of the engine together with fuel and environmental criteria. These stages have different load values in every stages of the flight process which is the most important cause of thrust changes in aircrafts. However, these parameters are directly related with the thermodynamics parameters of fuel and environmental conditions [2].

Aircraft engines are defined as propulsion cycles based on Brayton cycle. During this cycle, engine performance can be defined as the impulse power generated based on fuel consumed in the system. However, in this generation process, the combustion of fuel where fuel-air relationship and stoichiometric conditions in the combustion chamber are taken as basis effects of the greenhouse gas emissions, fossil fuel based CO_2 emissions being foremost. In addition, chemical reactions with direct effect on engine performance are parameters that directly affect impulse based thrust. Likewise, motor designer's aim is to ensure low weight, minimum fuel consumption and high thrust for high efficiency evaluations in engine designs. In this load distribution, especially for combustion procedures, the emission effect should be planned at minimum Thrust management

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indirectly provides engine performance control, flight safety being the foremost [3].

All these parameters are stand out the thermodynamic analysis in thrust performance. The transportation sector has about 25 % of energy consumption in the world. In addition, Fuel is the largest cost item more than the 30 % of the total operating cost for the global aviation industry, according to IATA (2010) in 2008 [4]. For these reasons, thermodynamic analysis methods should have applied on this area. In this context, Utlu and Hepbasli [5] reported that exergetic efficiency of the transportation sector in Turkey is 23.65 % in 2000 and it will be 28.85 % with increasing about 5 points in 2020. It can be realized that there is a great improvement potential through these low exergetic efficiency values. In another study, exergetic and energetic efficiencies, energy consumption rates and the exergo-economic parameters for various transportation methods such as roadway, airway, seaway was demonstrated in comparison with other countries [6].

Aviation is the most rapidly and continuously growing a transportation branch [7, 8]. Meanwhile, this rapidly growing indicates the increasing on energy demand. In this context, thermodynamic assessment of aircraft is an important issue in terms of improving efficiency within this area. In open literature, there are many studies based on thermodynamic analysis of aircraft engines. In power systems and thermal systems which are working depending on the combustion process, performance analysis is defined by exergy analysis. An exergetic analysis of a commercial aircraft for each flight period was performed [9]. Exergy efficiencies and exergy destruction rates were proved. Then performance characteristics were also examined according to these outputs. Amati et al. [10] have presented an exergy analysis of an advanced hypersonic vehicle with a twofold scope (an H2-fuelled engine and a scramjet with an on board kerosene reformer) by using CAMEL, a modular simulator. The exergetic variations of a gas turbine were investigated based on different operation conditions by Gogus et al. [11]. They revealed that the use of correction factors should be used both to determine exergy loses and destruction and to control volume changes according to environmental conditions. Design parameter effecting on energetic and exergetic characteristics of a turbojet engine were examined by Turan [12]. Effects of pressure ratio, specific fuel consumption and Mach number were considered in term of energetic and exergetic efficiency variations. In study made by Aydin [13], exergetic sustainability analysis of a LM6000 engine has been discussed. The researcher has defined the exergetic sustainability indicators in order to determine the sustainability aspects of a gas turbine engine based on power plant. Turgut et al. [14] have defined variable exergy destruction rates and exergetic efficiencies with altitudes by analysing each component of a turbofan engine. One of the studies on 3D flow is evaluation of exergy destruction and generated entropy through the fan and intake of a CF6-50 turbofan engine [15]. Another study related to the exergy analysis for gas cycle aircraft engines was made by Tona et al. [16]. They assessed overall engine performance throughout a complete mission by using chemical exergetic factors in their study. Researchers point out that the reference variable parameters in calculation. Wenjuan et al. [17] concluded that specific fuel consumption (SFC) increases with the rising of Mach number in a turbofan engine in case of high by-pass ratio thrust increases. Aydin et al. [18] evaluated a turboprop/turbo-shaft engine by using a component based approach. An engine used on helicopters and propeller aircraft is investigated under the various operating conditions. The changes of relative irreversibility, exergy efficiency, fuel depletion and productivity lack were presented according to the different loads. Tai et al. [19] developed a software used the genetic algorithm to optimise energy and exergy parameters of a two-spool turbofan engine. In study made by Atilgan et al. [20], exergo-environmental parameters of a turboprop engine in ground operations are examined. Aydin et al. [21] determined minimum and maximum exergetic efficiency of an engine by using the sustainability indicators of a turboprop engine for different flight periods. Aydin et al. [22] examined performance parameters such as specific fuel consumption, temperature and pressure distributions and exergy efficiencies of a turboprop at various loads in another study. Balli and Hepbasli [23] evaluated energetic and exergetic analysis of the overall engine and components for a T56 turboprop engine under different operating conditions.

Today, many studies are carried out on energy efficiency and exergy analysis issues in the area of sustainable aviation. However, as different from all studies, investigation of thrust effects on the exergetic performance based on the flight process has been very limited. The effects of thrust control and change in thrust on thermodynamic parameters are on a broad spectrum. In particular, undertaking of the thrust effect with the thermodynamic parameters is a different approach to fuel consumption and energy management. For this purpose, the effects of exergetic parameters depending on the thrust and then exergetic efficiency of a turbofan engine depending on aircraft characteristics were investigated under the different altitude conditions. This study shows that the effects of thrust performance including environmental parameters on the flight characteristics of the aircraft may change with reference to exergetic parameters and turbofan engine. This situation has a guiding influence in terms of the development of dynamic models in flight process. The study includes thrust management in aircraft, mathematics of exergetic analysis and performance analysis made for a turbofan engine in flight process.

Thrust management

Fuel consumption is associated with the obtained thrust in the system such as all power systems and the engines. Aircraft engines are typically defined in two different models. These are basically classified as piston engines and turboprops. But, while a turboprop engine is described as a turbine engine that drives an aircraft propeller, a turbojet employs exhaust gases. Efficiency parameters for all engine performances are points to be considered in the design process. Indeed, the design process actually done considering a two-stage cycle analysis [24]. In the design process; performance parameters of parametric cycle analysis (specific thrust and specific fuel consumption) design constraints (maximum turbine inlet temperature, fuel lower heating value) and design choices (fan and compressor pressure ratio, by-pass ratio, etc.) should be able to relate as functional. But the thrust loads for parametric cycle analysis in the design processes should be determined. Thrust values change according to mission profiles of aircraft in other words according to the purposes of usage. In other words, use of the aircraft for civilian or military purposes will be effects on the thrust and indirectly parametric cycle analysis. Thrust changes in aircraft depend to exit speed from nozzle of fluid entering the engine. Of course, it should be aimed low fuel consumption for high thrust in these changes. It also is meant to be high overall efficiency of the engine [25]. Flight process of the aircraft has a variable thrust effect depending on altitude. This change is defined in The Airplane Information Management System (AIMS) of aircraft. Flight process for a passenger aircraft is seen in Figure 1.

AIMS which contains many of the control systems unlike other vehicles is the brain of aircraft. However, AIMS also can be seen as a management program. The system's architecture structure provides important control on aircraft knowledge and management infrastructure [27]. Effects provided by this control system in aircrafts are shown in Figure 2.

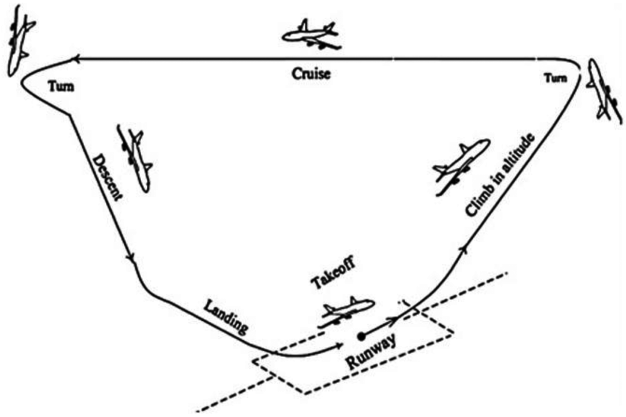

Figure 1: Typical flight phases for a passenger airplane [26].

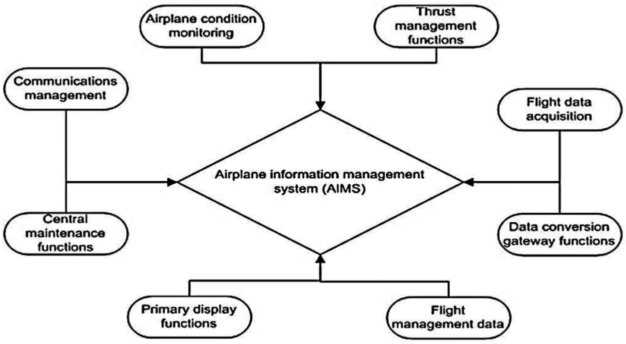

Figure 2: Supplied of AIMS in aircrafts [27].

AIMS in aircraft is important in terms of especially flight safety. AIMS manages the engine for producing enough thrust according to the environmental conditions including different altitude conditions. These values are determined by the results of the test procedure defined separately for each type of aircraft and engines, taking into account national aviation standards. In flight process, sufficient thrust conditions of the aircraft for all altitudes are formed based on the load parameters besides speed and altitude with AIMS. An aircraft has speed parameters changing with altitude up from static thrust for zero velocity to maximum thrust in flight process. For instance, the thrust change depending on the altitude for a turbofan engine is shown in Figure 3.

Flight process is faced with different fuel consumption for different thrust requirements at different altitude conditions. Because the weight of the aircraft will be decreased depending on fuel consumption during flight period, the needed thrust will also change. All these structures including test procedures are managed by thrust management under control of the AIMS. Energy consumption for the thrust load in all the load

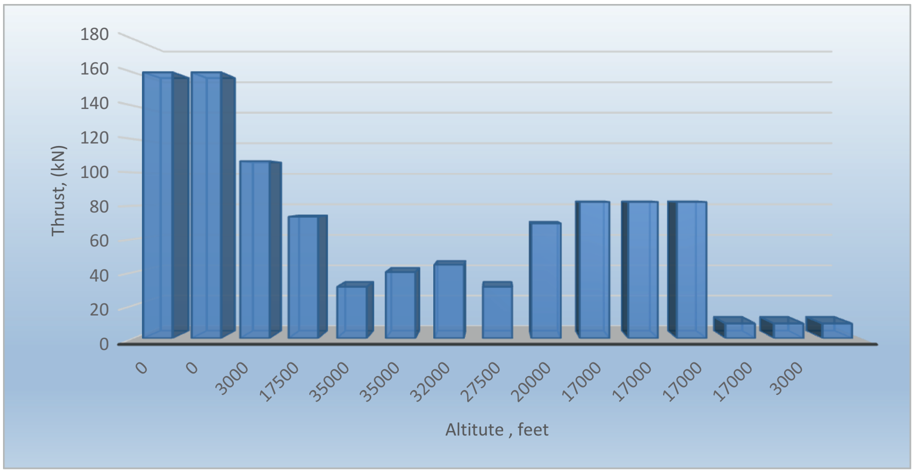

Figure 3: Thrust changes based on altitude.

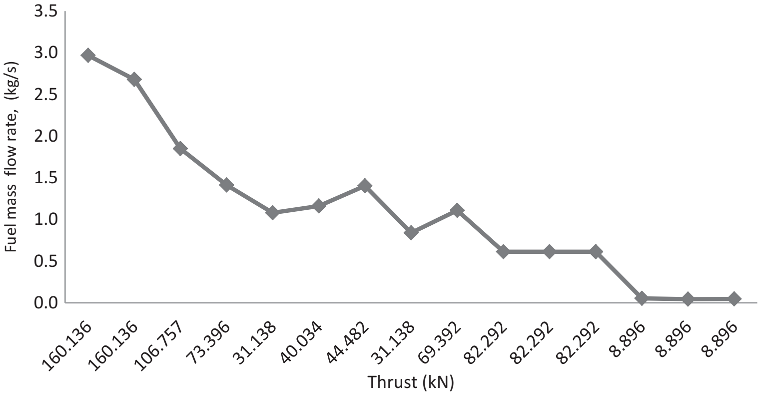

Figure 4: Fuel consumption based on thrust.

distribution affects the efficiency of the engine indirectly. Indeed, relationship between a turbofan's fuel consumption and the thrust load is given in Figure 4.

Figures 3 and 4 demonstrate the importance of thrust management in terms of flight safety and energy management. Indeed, it is seen that fuel consumption show a non-linear change based on the effects of the altitude. In this aspect, this effect can be also defined as an increase or decrease in fuel demand depending on the thrust for various climate conditions as like it can be defined depending on a fault. The effect of this on the engine performance can be evaluated. In this study, variations of this effect were investigated according to the thermodynamic effects rather than aerodynamic effects as unlike the literature. In the next section, effects of thrust on energy efficiency were evaluated by using energy and exergy analysis.

Theoretical analysis

Aircraft engines are systems that require thermodynamic evaluation and they were evaluated with the first and second laws of thermodynamics, which were taken as references. The mass flows were investigated under the steady-state and steady-flow conditions [28, 29]. Accordingly the mass balance is,

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

where $\dot{m}$ notates the mass flow rate, *in* and *out* subscripts stand for inlet and outlet respectively. The overall energy balance of the engine under the steady-flow depends on the balance between the inlet and outlet energy loads [28, 29]. Accordingly overall energy balance is,

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

The maximum work which can be obtained as a measure of irreversibility depending on the second law of thermodynamics is defined as Exergy. Exergy is the sum of physical, chemical, kinetic and potential exergies in a system [30]. Accordingly total exergy is,

$$\dot{E}x = \dot{E}x_k + \dot{E}x_p + \dot{E}x_{ph} + \dot{E}x_{ch} \tag{3}$$

For environmental condition assumptions, kinetic and potential exergies are disregarded and defined as thermal exergy given in Eq. 4 [31]:

$$\dot{E}x_{th} = \dot{E}x_{ph} + \dot{E}x_{ch} \tag{4}$$

Exergy is destroyed due to the irreversibility of the thermal system. Exergy destruction is expressed by some parameters in exergy balance [28, 29]. These are described in the following equations;

$$\sum \dot{E}x_{in} - \sum \dot{E}x_{out} = \sum \dot{E}x_{dest} \tag{5}$$

$$\dot{E}x_{heat} - \dot{E}x_{work} + \dot{E}x_{mass,\,in} - \dot{E}x_{mass,\,out} = \dot{E}x_{dest} \tag{6}$$

$$\dot{E}x_{heat} = \sum \left(1 - \frac{T_0}{T}\right)\dot{Q} \tag{7}$$

$$\dot{E}x_{work} = \dot{W} \tag{8}$$

$$\dot{E}x_{mass} = \sum \dot{m}\psi \tag{9}$$

where $\dot{E}x_{dest}$, $\dot{E}x_{heat}$, $\dot{E}x_{work}$ and $\dot{E}x_{mass}$ notates exergy destruction rate, exergy rate of heat transfer, exergy rate of work and exergy rate of mass flow respectively. In flow process, the flow specific exergy (ψ) is derived as given below for flow parameters of system [32].

$$\psi = (h - h_0) - T_0(s - s_0) \tag{10}$$

where h is enthalpy and s is entropy whilst the zero subscript stands for dead state conditions. The entropy balance is calculated for a steady-state, steady-flow system as given following eq. (11) [28, 29].

$$\dot{S}_{in} - \dot{S}_{out} + \dot{S}_{gen} = 0 \tag{11}$$

It is possible to describe a quantity to be maximized in terms of the total entropy generation rate in a system. The lost available work is stated on the basis of The Gouy–Stodola theorem as given following eq. (12) [33]:

$$\dot{E}x_{dest} = T_0\dot{S}_{gen} \tag{12}$$

Second law efficiency of a steady-state, steady-flow system can be denoted as given following eq. (13) [28, 29]:

$$\eta_{Ex} = \frac{\dot{E}x_{out}}{\dot{E}x_{in}} = 1 - \frac{\dot{E}x_{dest}}{\dot{E}x_{in}} \tag{13}$$

It is possible to achieve maximum improvement in the exergy efficiency of a system, if the exergy loss or irreversibility is minimized. Therefore, improvement potential rate for exergetic assessment of a system is defined as bellow in eq. (14) [30]:

$$I\dot{P} = (1 - \eta_{Ex})\left(\sum \dot{E}x_{in} - \dot{E}x_{out}\right) \tag{14}$$

System definition and assumptions

Thrust management discussed in this study is presented to show that the thrust effects on flight process for all aircraft can be managed with the aspect of energy efficiency including aerodynamic control in terms of the sustainable aviation. The study, in this regard, is modelled with reference to the actual flight parameters of a turbofan engine taken as model. Selected engine is turbofan engine with a high bypass ratio which has expanding usage area in aircrafts such as Boeing 767–200, B747 and the Airbus A300 and A310 [34]. Structural features and components of the engine are given in Figure 5.

These engines have a high bypass ratio, and this effect has an impact improving the structural performance. F (fan), LPC and HPC (low and high pressure compressors), CC (annular combustion chamber), HPT (high pressure turbine) and LPT (low pressure turbine) are main core components of the turbofan engine. The

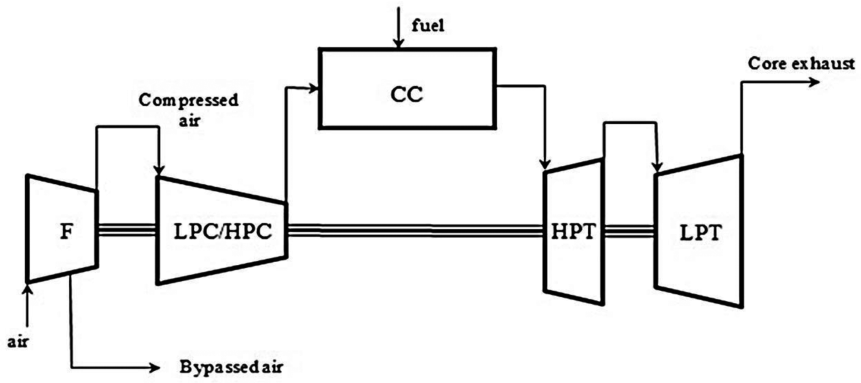

Figure 5: Turbofan engine main components.

engine has a thrust range from 8.89 kN to 160.36 kN depending on flight stages. In the process, the aircraft fuel range is 0.044–2.97 kg/s. Altitude range for undertaking aircraft is 0–35,000 feet and atmospheric temperature range is 224.62–288 K. In the study, investigation has been made taking into account atmospheric conditions the engine's faced depending on altitude conditions. To take into consideration in the analysis, some assumptions have been made and these have been given below.

- The turbofan engine is operated under steady-state, steady conditions.
- Two separated air compressors of engine are assumed to be integrated.
- Two separated gas turbines of engine are assumed to be integrated.
- The compressor and gas turbine parts of engine are considered as adiabatic.
- The bleed air flow used to cool the gas turbine section is neglected.
- Considering adiabatic conditions in the combustion chamber, the pressure drop is neglected.
- In the analysis, kinetic energy or exergy and potential energy or exergy effects are neglected.
- Pressure and temperature values in the dead state conditions are considered variable depending on the effects at atmospheric conditions.

Results and discussion

In this study, performance analysis of turbofan engine were made based on the first and second laws of thermodynamics depending on the fuel consumption and especially trust changes under various altitude conditions. In the analysis, air parameters and thermo-physical features in each altitude are taken into consideration before from investigation of thrust effect. Firstly, the energy and exergy efficiency and improvement potential of the engine are calculated for each altitude. According to turbofan engine in Figure 5, the air parameters and thermo-physical features used in analyses are determined and the data are given in Table 1.

Thrust management in a turbine can be evaluated as energy consumption depending on the fuel consumption and power control. Indeed, energy efficiency and thrust can be managed by control of altitude. For this purpose, it has been studied energy load variations according to altitude changes for turboprop taken as reference; and load changes are given in Figure 6.

Since the aircraft's climb condition (altitude 3,000 feet) changes in energy demand does not have a linear effect. In this sense, changing energy demand of turbine will directly affect on thrust. Energy load and turbine energy changes were examined based on various altitudes and results were given Figure 7.

The balance between energy and thrust based on altitude conditions is important in terms of management thrust. Especially, between 17,500 feet and 20,000 feet, variation rate is over 20 %. It is noteworthy aspect of the thrust. In this regard, thrust and power relations will generate a similar variation in terms of fuel consumption. The energy consumption performance of the turbine and variation in thrust were examined according to this distribution and then the results of efficiency were given in Figure 8.

When the thrust variation is considered until from take-off to maximum Mach, the energy efficiency ranges from 42.8 % to 36.7 %. When the thrust especially in the level of 40s% is taken into consideration, fuel

Table 1: The air parameters and thermo-physical features based on altitude.

Parameters	Altitude (feet)							
	0	3,000	35,000	27,500	20,000	17,000	3,000	0
Mach	0.186	0.401	0.86	0.72	0.83	0.34	0.24	0.27
Air velocity (m/s)	56.58	129.11	141.97	141.97	191.35	82.81	78.70	82.30
Atm pressure (kPa)	101.3	90.82	37.11	41.84	46.56	60.75	90.82	101.33
High pressure (kPa)	2,958.57	2,652	1,083	1,221	1,359	1,773	2,652	2,958
Air mass flow (kg/s)	161.4	100.6	58.71	45.68	60.33	2.89	2.39	2.52
Fuel mass flow (kg/s)	2.97	1.85	1.08	0.84	1.11	0.05	0.04	0.05
Fan inlet temp. (K)	288.1	282.06	278.08	233.53	248.38	254.32	282.06	288.15
HPC outlet temp. (K)	695.4447	698.92	770.61	632.74	692.27	626.05	684.43	700.9
Fuel inlet temp. (K)	288.2	288.2	288.2	288.2	288.2	288.2	288.2	288.2
LPT outlet temp. (K)	501.3	473.0	486.9	547.3	452.4	546.8	512.2	495.9

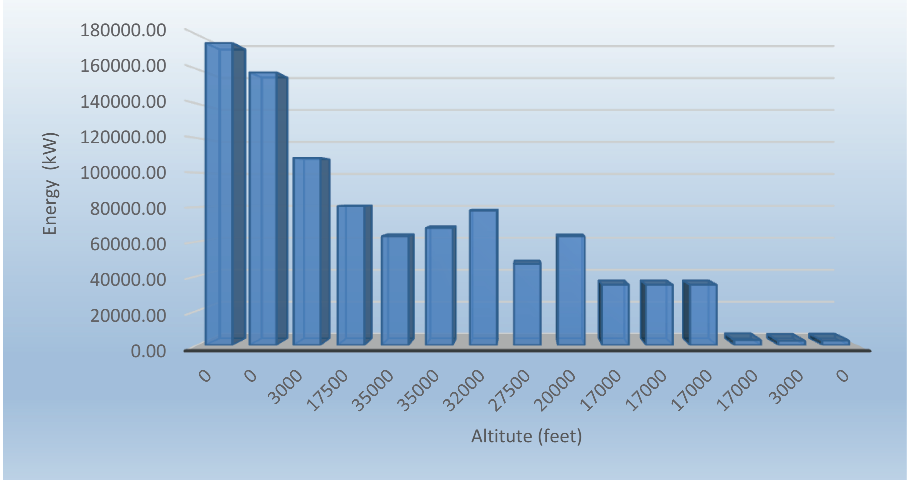

Figure 6: Energy load variations based on altitude.

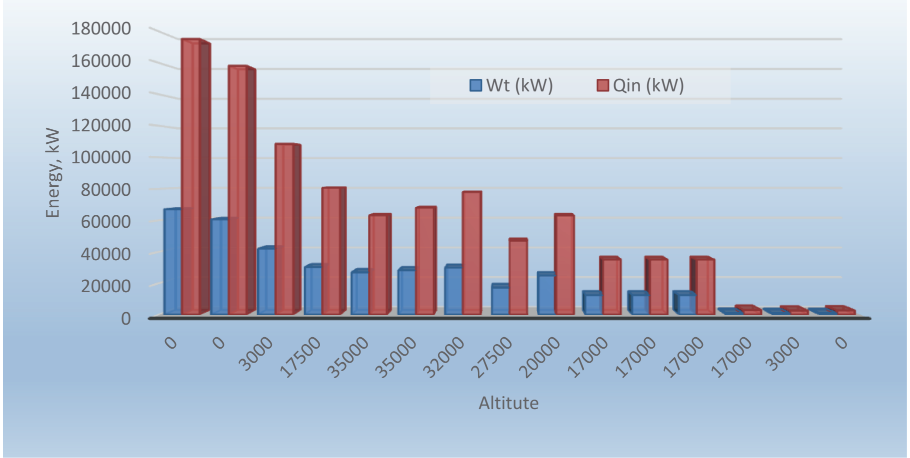

Figure 7: Energy load and thrust changes based on various altitudes.

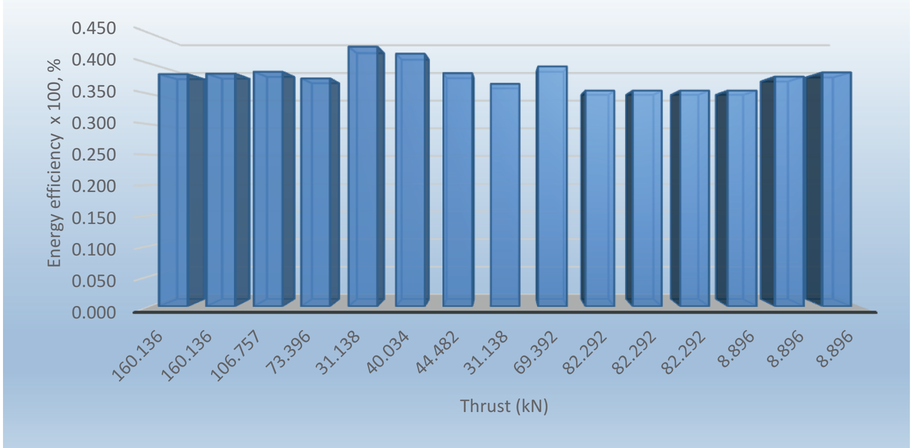

Figure 8: Energy efficiency variations based on thrust.

consumption and efficiency can be reduced by high thrust generate at low altitude.

In the performance evaluation, another parameter is exergy analysis method which can be questioned irreversibility and entropy production. Thrust changes can be questioned aspect of the entropy production. Exergy efficiency was examined based on the thrust, and the results were given in Figure 9.

Average exergy efficiency of the engine was found as 23.72 %. From take-off (160.136 kN) to maximum Mach (69.392 kN) in the engine, exergy efficiency is demonstrate non-linear distribution. For this reason, all of main components should be considered separately. As seen in Figure 9, max exergy destruction occurred in take off period due to unavoidable losses.

Exergy efficiency also shows that the power doesn't directed as proper. Particularly, distribution in engine performance is describing improvement potential. Figure 10 shows this effect.

When the thrust changes in engine were considered, average improvement potential was found as 59.11 % in theory. In addition, for specific fuel consumption (SFC), there are still 30 % improvements potential. ICAO 2010 report [35] is being pointed to a reduction in fuel consumption trends and it is expected to drop below 4 liters per pax / 100 km in 2020.

Conclusion

In this study, especially in turboprop engines, it is seen that thrust control can be oriented by energy and exergy performances, in addition to the dynamic effects. Energy and especially exergy efficiencies can help to control the thrust management in terms of controlled fuel consumption in addition to outside the flight security. According to the results, the improving of the engine efficiency by the thrust control will decrease greenhouse gas emissions

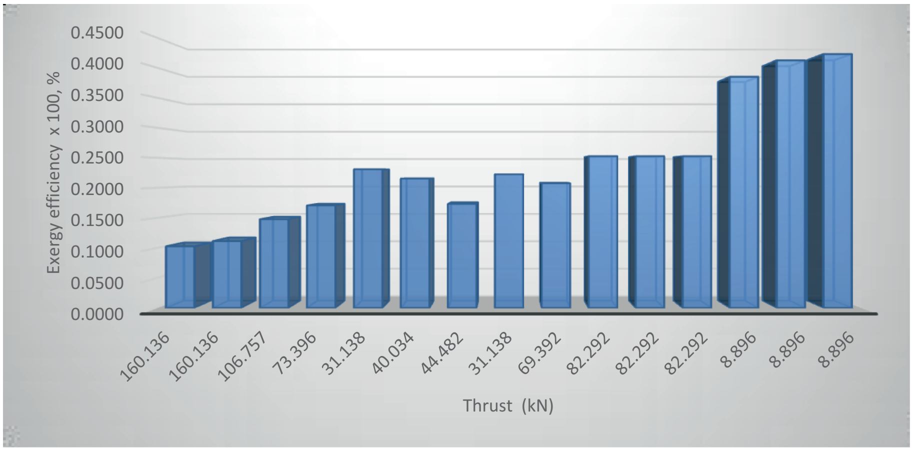

Figure 9: Exergy efficiency based on thrust changes.

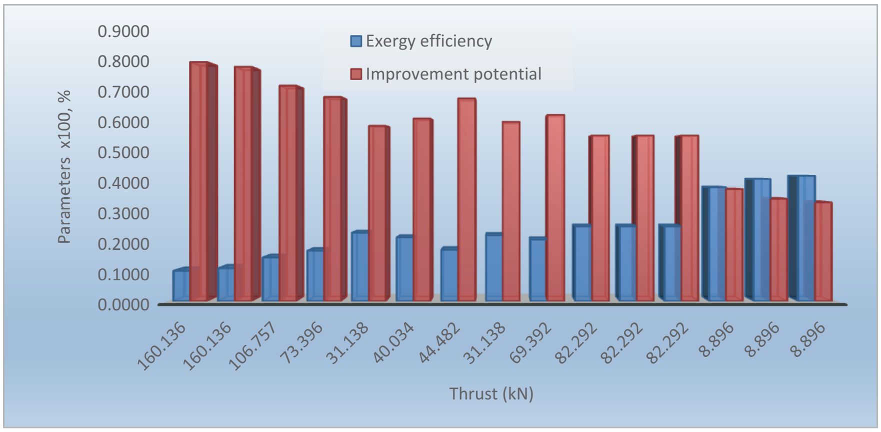

Figure 10: Improvement potential according to thrust.

by reducing entropy production based on the improvement potential.

In this study, a turbofan engine is assessed thermodynamically and some exergetic parameters are introduced. As a result of this study, observations are as follows;

- The maximum exergy destruction is produced by the combustion chamber. Meanwhile, the lowest exergy destruction is found in the gas turbine component. In this context, the maximum improvement potential is the greatest in the combustion chamber components with about 80 %. Thus, avoidable and unavoidable losses should be considered separately.
- In the analysis of a turbofan engine which were altitude-dependent consumption values taken as reference, similar changes were observed between thrust and thermodynamics parameters.
- Fuel consumption based on thrust is in take-off position because of greatest thrust needs and it is directly proportional with efficiency.
- A turbofan engine which can be described as a compromise between turboprop and turbojet engines and can fly at transonic speeds (up to Mach 0,9) is feasible for optimization based on thermodynamic approaches.

This study will make a positive contribution to productivity and sustainability in terms of environmental impact. For a future study, it is possible to determine effective circumstances in terms of environmentally and sustainability indices of the turbofan engine in the same conditions.

Nomenclature

AIMS	The Airplane Information Management System
CC	combustion chamber
c_p	specific heat, kJ/(kg K)
$\dot{E}$	energy rate, kW
$\dot{Ex}$	exergy rate, kW
F	fan
h	specific enthalpy, kJ/kg
HGT	high pressure gas turbine
HPC	high pressure compressor
ICAO	International Civil Aviation Organization
$\dot{IP}$	improvement potential, %
K	Kelvin
LGT	low pressure gas turbine
LPC	low pressure compressor
$\dot{m}$	mass flow rate, kg/s
P	pressure, kPa
s	specific entropy, kJ/(kgK)
$\dot{S}$	entropy rate, kW
T	temperature, K
$\dot{W}$	work rate, kW

Greek Letters

ψ	specific exergy, kJ/kg
η	efficiency

Subscripts

0	reference conditions
ch	chemical
dest	destruction
Ex	exergy
f	fuel
gen	generated
heat	thermal
in	inlet section
k	kinetic
mass	mass flow
out	outlet section
p	potential
ph	physical
work	work

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