Pages: 35-46/ Vol. 15/ No.2 / Summer- Fall 2022

Journal of Aerospace Science and Technology

www:jast.ias.ir

Scienctific – Research Article

Thermodynamic Analysis of a Three-Spool Mixed-Flow Turbofan: An Approach to Improve Burner Performance

Sarallah Abbasi [1], **Mohammad Amin Daraee** [2]

1 - 2- Arak University of Technology, Mechanical Engineering Department

ABSTRACT

Keywords: *Turbofan, Energy and Exergy Analysis, Parametric Study, Burner Exergy Efficiency*

A nonlinear model has been developed and implemented in the Simulink environment and This research studies the thermodynamic analysis of a three-spool mixed-flow turbofan engine by examining different parameters, including flight altitude, flight Mach number, fan pressure ratio, high and Intermediate-pressure compressor pressure ratios, bypass ratio, and burner exit temperature. First, the effect of these parameters on the thrust, thrust-specific fuel consumption (TSFC), and engine efficiency was investigated. The exergy analysis resulted in the finding that the lowest exergy efficiency belongs to the combustion chamber, with a value of 85.45%. Therefore, a parametric study was conducted to improve the burner's performance and exergy efficiency. In particular, in the case of a bypass ratio of 2.2 and a fan pressure ratio of 2, the exergy efficiency of the burner is increased by 12.23% compared to the base case. In addition, the sensitivity analysis results show that the burner exit temperature and the high-pressure compressor pressure ratio of 21.81 and 2.2%, respectively, have the most and the least effect on the engine net thrust. Moreover, the burner exit temperature and the flight altitude of 4.57% and 0.11%, respectively, have the most and the least effect on the TSFC.

Nomenclature

A	Area, (m^2)
C_p	Isobaric Specific Heat Capacity, (kJ/kg.K)
$\dot{Ex}$	Exergy Rate, (W)
F	Thrust, (N)
h	Enthalpy, (kJ/kg)
$\dot{IP}$	Improvement Potential Rate, (MW)
M	Mach Number
$\dot{m}$	Mass Flow Rate, (kg/s)
P	Pressure, (Pa)
Q_H	Heating Rate, (W)
s	Entropy, (kJ/kg.K)
T	Temperature, (K)
V	Velocity, (m/s)
$\dot{W}$	Power, (W)
Greek letters	
α	Bypass Ratio
δ	Fuel Depletion Ratio
ε	Specific Exergy, (kJ/kg)
η	Efficiency
ρ	Density, (kg/m^3)
χ	Relative Exergy Destruction
Subscripts	
0	Ambient Condition
C	Turbofan Core

1 Assistant Professor (Corresponding Author) **Email: *** s_abbasi@arak.ac.ir

2 Msc.

DOI: 10.22034/jast.2022.340613.1117

Submit: 04.05.2022 / Accepted: 18.11.2022

Print ISSN:1735-2134 Online ISSN: 2345-3648

CC	Combustion Chamber
ch	Chemical
D	Destructed Exergy
F	Bypass Duct
f	Fuel
kn	Kinetic
pt	Potential
ph	Physical
prop	Propulsive
pr	Produced
th	Thermal

Introduction

Turbofan engines are a type of gas turbine-based engine used in many passenger and military aircraft. The distinctive feature of this engine is a fan at the intake that causes air to flow from the bypass duct around the engine core and exit at high speed. This causes more thrust force generation and less fuel consumption. Turbofan engines are applicable at intermediate speeds (up to Mach 2) and can fly with low fuel consumption and low heat generation for an extensive period at altitudes close to the earth's surface. Accordingly, the first step in designing a turbofan engine is to analyze the thermodynamic cycle and study the design and performance parameters of the engine. Analyzing these parameters is essential for accomplishing design targets, including performance improvement. Researchers in this field have always attempted to design engines to reduce fuel consumption to the least possible amount with the highest efficiency and thrust generation. Enhancing the design and performance of these engines leads to lower energy consumption and waste, higher efficiency, and better environmental protection.

In recent decades, extensive research has been conducted on thermodynamic analysis, including jet engine energy and exergy analysis. For example, Balli et al. [1] studied a turboprop engine energy and exergy analysis and the effect of various operating conditions on engine performance. Aidin et al. [2] and Sohert et al. [3], in separate studies, investigated the exergy analysis of turbofan engines, the exergy analysis parameters for different engine components, and the identification of components with the lowest and highest exergy efficiencies. Tona et al. [4] studied exergy and thermo-economic analysis for a turbofan engine during different flight phases to investigate exergy analysis parameters in each flight phase. In some other research, the effects of changes in different parameters on jet engine performance have been studied. Yadav et al. [5] and El-Sayed et al. [6], in separate studies, conducted parametric studies to evaluate the effect of design parameters and operating conditions on the output of turbofan engines. Some other researchers have examined the effects of equipment such as secondary combustion chambers on engine performance. Liew et al. [7] investigated the effect of an inter-stage turbine burner on the cycle analysis performance of a turbofan engine. Liu et al. [8] conducted studies to improve turbojet and turbofan engine performance by applying inter-turbine burners. In another research category, optimization methods such as genetic algorithms have been used to improve engine performance. Asako et al. [9] used a multidisciplinary design optimization technique to conceptualize an aircraft engine. Atashkary et al. [10] used a multi-objective genetic algorithm to optimize the design of the thermodynamic cycle of a turbojet engine. Homifar et al. [11] and Choi et al. [12], in separate studies, performed parametric studies for important parameters of a turbofan engine and then optimized engine performance using a genetic algorithm.

Turan et al. [13] performed an exergy analysis and stability criteria for a high-bypass turbofan engine. Exergy stability calculations were conducted and the stability criteria of the engine were calculated and analyzed. Consequently, the engine exergy efficiency was calculated as approximately 29.6%. The results showed that the combustion chamber had the lowest exergy efficiency of 76.1% and the highest exergy destruction rate of 72.8%. In contrast, the high-pressure turbine had the highest exergy efficiency (95.8%) and the lowest exergy destruction rate (4.5%). Moreover, the highest percentages of productivity lack belonged to the combustion chamber, compressor, and fan, respectively. Moreover, in another study [14], the author examined the effects of flight Mach number on the thermodynamic efficiency of an unmanned airplane turbojet engine. This study examined the effects of different aircraft speeds in a fixed reference environment at a flight altitude of 8000 meters and studied the change in Mach number on engine efficiency and performance. Moreover, Balli et al. [15] conducted research that analyzed the exergy of a turbofan engine. This study showed that the highest exergy efficiency belonged to the high-pressure turbine (98.23%) and the highest relative exergy destruction occurred in the combustion chamber (74.53%). In addition, the combustion chamber exhibited the lowest exergy efficiency of 72.38%. The analysis in this study indicates that the lowest efficiency belongs to the combustion chamber because of the irreversibility of the combustion process, chemical reactions, heat transfer, friction, and disturbances. One suggested method is to preheat the reactants, which can decrease exergy destruction to a certain extent. Furthermore, another study [16] analyzed and assessed the exergetic stability of a high-bypass turbofan engine. The turbofan engine studied in this research was from engines used in long-range commercial airplanes. This research examined different exergy analysis parameters, including exergy efficiency, losses and destruction, environmental effect factor, ecological effect factor, and other parameters related to exergy analysis. The lowest exergy efficiency (63.86%), and highest relative exergy destruction (71.49%) were observed in the combustion chamber. Turgut et al. [17] studied the effects of modifying the isentropic efficiency of different engine components on exergy efficiency and exergy destruction. In addition, this study aimed to determine the irreversibility of engine components. According to this research, the engine bypass and the main exhaust have exergy waste rates of 47.3 and 53.9 megawatts, respectively. In addition, the combustion chamber, with an exergy destruction rate of 31.5 megawatts, was the most irreversible component of the engine. The results of this study indicate that an increase in the isentropic efficiency of the fan, compressor, and turbine leads to higher costs but less exergy destruction. Altuntas et al. [18] conducted an energy and exergy analysis and assessed the stability of helicopter engines with different powers from 150 to 600 horsepower. This study examined different energy and exergy analysis parameters to improve engine performance, reduce waste and fuel consumption and reduce environmental pollution. This study showed that an engine with 250 horsepower resulted in the highest energy efficiency, exergy efficiency, and exergetic stability index and the lowest ratio of exergy waste, exergy destruction coefficient, and environmental effect factor. Goodarzi et al. [19] conducted energy and exergy analyses of a turboprop engine under different working conditions. In this research, different working conditions, including flight altitude and Mach number, were modeled, and engine performance was studied under different conditions, particularly from the perspective of exergy analysis. The results of the thermodynamic analysis indicate a reduction in power and an increase in fuel consumption owing to an increase in altitude and flight Mach number. In addition, exergy analysis showed that an increase in flight Mach number causes an increase in engine exergy efficiency and exergy efficiency of the combustion chamber. However, it reduces the exergy efficiency of the compressor and turbine. In addition, the results of the exergy analysis of different engine components indicate that the combustion process was the dominant factor in the irreversibility of the turboprop engine. Dinc [20] investigated the effects of different parameters on the amount of NOx pollution produced in a turbofan engine related to an unmanned aircraft. This study examined the effect of flight Mach number, intake air temperature, and flight altitude on the production of nitrogen oxide pollution and the production change process of engine power generation. Elbadawy et al. [21] studied the effects of different parameters on turbofan engine performance and the pollution produced. This research studied the effect of altitude and flight Mach number on the amount of engine power generation and emissions such as CO2 and NOx and their effect on global warming.

Most previous research studied unmixed-flow turbofans and other types of jet engines, such as turbojets and turboprops. In addition, a few parameters have been investigated in most of these studies. In this study, a three-spool mixed-flow turbofan has been modeled. In addition, the effects of the most important effective parameters have been investigated for energy and exergy analysis. These parameters include altitude, flight Mach number, fan pressure ratio, HPC and IPC pressure ratios, bypass ratio, and burner exit temperature. Moreover, the exergy analysis parameters of different engine components were investigated to identify low-efficiency parts and high exergy losses. After it was found that the burner had the lowest exergy efficiency and the highest exergy destruction rate, a parametric study was conducted to improve its performance and exergy efficiency. Subsequently, the effects of different parameters on improving the burner exergy efficiency were evaluated.

Governing equations

Energy analysis and performance parameters

In this study, the incoming airflow passes through the engine core and bypass duct separately. Figure (1) shows a schematic of the turbofan components studied in this research. Table (1) lists different air passage stations inside the engine.

The mass, energy, and exergy balance equations are defined according to Equations (1-3) [1,22].

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

$$\sum \dot{m}_{in} h_{in} + \sum \dot{W}_{in} = \sum \dot{m}_{out}\, h_{out} + \sum \dot{W}_{out} \quad (2)$$

$$\sum \dot{Ex}_{in} - \sum \dot{Ex}_{out} = \sum \dot{Ex}_{D} \quad (3)$$

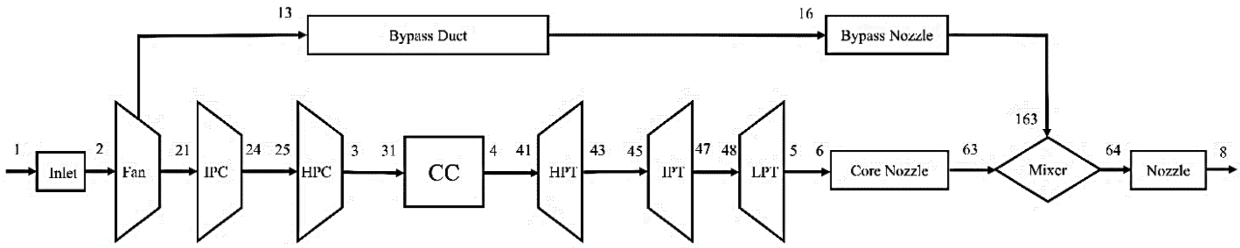

Figure 1- Station numbering of the investigated turbofan

Table 1- air passage stations inside the engine

0	Ambient Air
1	Engine Inlet
2	Fan Inlet
13	Bypass Duct Inlet
16	Bypass Nozzle Inlet
163	Bypass Nozzle Outlet
21	IPC1 Inlet
24	IPC Outlet
25	HPC2 Inlet
3	HPC Outlet
31	Burner Inlet
4	Burner Outlet
41	HPT3 Inlet
43	HPT Outlet
45	IPT4 Inlet
47	IPT Outlet
48	LPT5 Inlet
5	LPT Outlet
6	Turbofan Core Nozzle Inlet
63	Turbofan Core Nozzle Outlet
64	Mixer Nozzle Inlet
8	Mixer Nozzle Outlet

Mass flow rate is generally written as Equation (4), where ρ is the ambient air density, V is the airflow velocity, and A is the area.

$$\dot{m} = \rho A V \quad (4)$$

The bypass ratio is defined as Equation (5), where $\dot{m}_F$ is the air mass flow rate passing through the bypass duct and $\dot{m}_C$ is the air mass flow rate passing through the engine core.

$$\alpha = \frac{\dot{m}_F}{\dot{m}_C} \quad (5)$$

The total mass flow rate equals the sum of the bypass duct and the turbofan core flow rates.

$$\dot{m} = \dot{m}_C + \dot{m}_F = (1+\alpha)\dot{m}_C \quad (6)$$

In mixed-flow turbofan engines, thrust is defined as Equation (7). Where V_e is the outlet nozzle airflow velocity, V_0 is the flight velocity, A_e is the outlet nozzle cross-sectional area, P_e is the outlet nozzle airflow pressure and P_o is the ambient air pressure [23].

$$F = \dot{m}(V_e - V_o) + A_e(P_e - P_o) \quad (7)$$

Thrust-specific fuel consumption (TSFC) is defined according to Equation (8) as the ratio of fuel mass flow rate consumed in the burner to the total thrust of the turbofan engine.

$$TSFC = \frac{\dot{m}_f}{F} \quad (8)$$

1. Intermediate-Pressure Compressor
2. High-Pressure Compressor
3. High-Pressure Turbine
4. Intermediate-Pressure Turbine
5. Low-Pressure Turbine

Fuel heating value (*FHV*) is defined as the ratio of the heating rate to the fuel mass flow rate consumed in the burner.

$$FHV = \frac{Q_H}{\dot{m}_f} \tag{9}$$

Where Q_H is the heating rate given to the air in the burner and is defined according to Equation (10). Where C_p is the isobaric-specific heat capacity and T_{31} and T_4 are the flow temperatures at the burner inlet and outlet, respectively.

$$Q_H = \dot{m}_f C_p (T_4 - T_{31}) \tag{10}$$

propulsive efficiency (η_{prop}) is defined as the multiplication of thrust in flight velocity divided by the kinetic energy rate.

$$\eta_{prop} = \frac{2FV_0}{\dot{m}_0 (V_e^2 - V_o^2)} \tag{11}$$

Thermal efficiency (η_{th}) can be written as the ratio of the engine's kinetic energy rate to the thermal energy rate of the fuel.

$$\eta_{th} = \frac{\dot{m}_0 (V_e^2 - V_o^2)}{2Q_H} \tag{12}$$

The overall efficiency ($\eta_{overall}$) is obtained by combining the propulsive and thermal efficiencies [24].

$$\eta_{overall} = \eta_{th} . \eta_{prop} = \frac{FV_0}{Q_H} \tag{13}$$

Exergy analysis parameters

According to Equation 14, if a system is not affected by the effects of electricity, magnetism, nuclear, and surface tension, then Its total flow exergy will consist of the four components Ex_{ph}, Ex_{ch}, Ex_{kn}, and Ex_{pt}, which represent physical, chemical, kinetic and potential exergy, respectively. Based on the steady-state conditions for a control volume with a mass flow rate equal to $\dot{m}$, the total exergy rate of the system is defined as Equation 15.

$$Ex = Ex_{ph} + Ex_{ch} + Ex_{kn} + Ex_{pt} \tag{14}$$

$$\dot{Ex} = \dot{m}(\varepsilon_{ph} + \varepsilon_{ch} + \varepsilon_{kn} + \varepsilon_{pt}) \tag{15}$$

Kinetic and potential exergies can be assumed to be negligible. Therefore, the specific physical exergy can be defined as Equation 16. According to the ideal gas expression and with constant specific heat capacity, it can be written as Equation 17.

$$\varepsilon_{ph} = (h - h_0) - T_0(s - s_0) \tag{16}$$

$$\varepsilon_{ph} = C_p(T - T_0) - T_0[C_p \ln\left(\frac{T}{T_0}\right) - Rln(\frac{P}{P_0})] \tag{17}$$

for liquid fuels ($C_x H_y O_z S_\sigma$), the specific chemical exergy is defined as Equation 18.

$$\varepsilon_{ch,f} = LHV[1.0401 + 0.01728\frac{y}{x} + 0.0432\frac{z}{x} + 0.2196\frac{\sigma}{x}(1 - 2.0628\frac{y}{x})] \tag{18}$$

Exergy analysis of turbofan engines includes several parameters such as exergy efficiency, exergy destruction rate, improvement potential, relative exergy destruction, and fuel depletion ratio, which are defined according to Equation (19-23) for the *i'th* component of the turbofan engine [1,3].

$$\eta_{ex} = \frac{\dot{Ex}_{pr}}{\dot{Ex}_f} \tag{19}$$

$$\dot{Ex}_D = \dot{Ex}_{in} - \dot{Ex}_{out} \tag{20}$$

$$\dot{IP} = (1 - \eta_{ex})\dot{Ex}_D \tag{21}$$

$$\chi = \frac{\dot{Ex}_D}{\sum \dot{Ex}_D} \tag{22}$$

$$\delta = \frac{\dot{Ex}_D}{\sum \dot{Ex}_f} \tag{23}$$

Exergy analysis for turbofan engine components

Equations (24-48) represent the equations of mass, energy conservation, and exergy efficiency for the main components of the turbofan engine [1,2].

Fan:

$$\dot{m}_2 = \dot{m}_{13} + \dot{m}_{21} \tag{24}$$

$$\dot{W}_{fan} - \dot{m}_{13}h_{13} - \dot{m}_{21}h_{21} + \dot{m}_2 h_2 = 0 \tag{25}$$

$$\eta_{ex,fan} = \frac{\dot{Ex}_{13} + \dot{Ex}_{21} - \dot{Ex}_2}{\dot{W}_{fan}} \tag{26}$$

IPC:

$$\dot{m}_{21} = \dot{m}_{24} \tag{27}$$

$$\dot{W}_{IPC} + \dot{m}_{21}h_{21} - \dot{m}_{24}h_{24} = 0 \tag{28}$$

$$\eta_{ex,IPC} = \frac{\dot{Ex}_{24} - \dot{Ex}_{21}}{\dot{W}_{IPC}} \tag{29}$$

HPC:

$$\dot{m}_{25} = \dot{m}_3 \quad (30)$$
$$\dot{W}_{HPC} + \dot{m}_{25}h_{25} - \dot{m}_3h_3 = 0 \quad (31)$$
$$\eta_{ex,HPC} = \frac{\dot{Ex}_3 - \dot{Ex}_{25}}{\dot{W}_{HPC}} \quad (32)$$

Bypass duct:

$$\dot{m}_{13} = \dot{m}_{163} \quad (33)$$
$$\dot{m}_{13}h_{13} - \dot{m}_{163}h_{163} = 0 \quad (34)$$
$$\eta_{ex,Bypass} = \frac{\dot{Ex}_{163}}{\dot{Ex}_{13}} \quad (35)$$

Combustion chamber:

$$\dot{W}_{CC} = 0 \quad (36)$$
$$\dot{m}_{31} + \dot{m}_f = \dot{m}_4 \quad (37)$$
$$\dot{m}_{31}h_{31} + \eta_{CC}\dot{m}_f LHV = \dot{m}_4h_4 \quad (38)$$
$$\eta_{ex,CC} = \frac{\dot{Ex}_4}{\dot{Ex}_{31} + \dot{Ex}_{fuel}} \quad (39)$$

HPT:

$$\dot{m}_{41} = \dot{m}_{43} \quad (40)$$
$$-\dot{W}_{HPT} + \dot{m}_{41}h_{41} - \dot{m}_{43}h_{43} = 0 \quad (41)$$
$$\eta_{ex,HPT} = \frac{\dot{W}_{HPT}}{\dot{Ex}_{41} - \dot{Ex}_{43}} \quad (42)$$

IPT:

$$\dot{m}_{45} = \dot{m}_{47} \quad (43)$$
$$-\dot{W}_{IPT} + \dot{m}_{45}h_{45} - \dot{m}_{47}h_{47} = 0 \quad (44)$$
$$\eta_{ex,IPT} = \frac{\dot{W}_{IPT}}{\dot{Ex}_{45} - \dot{Ex}_{47}} \quad (45)$$

LPT:

$$\dot{m}_{48} = \dot{m}_5 \quad (46)$$
$$-\dot{W}_{LPT} + \dot{m}_{48}h_{48} - \dot{m}_5h_5 = 0 \quad (47)$$
$$\eta_{ex,LPT} = \frac{\dot{W}_{LPT}}{\dot{Ex}_{48} - \dot{Ex}_5} \quad (48)$$

Validation

The engine investigated in this study is a mixed-flow turbofan engine that is modeled using the EES code. The initial inputs for modeling the turbofan engine in the base case are listed in Table (2).

Table 2- The initial inputs for modeling the turbofan [25]

Parameters	**Value**
Flight Altitude (m)	16000
Flight Mach Number	1.6
Intake Pressure Ratio	0.9543
Outer Fan Pressure Ratio	2.44
Inner Fan Pressure Ratio	2.44
IPC Pressure Ratio	4.839
HPC Pressure Ratio	3.85
Design Bypass Ratio	2.75
Bypass Duct Pressure Ratio	0.97
Burner Exit Temperature (K)	1823.61
Burner Design Efficiency	0.997
Fuel Heating Value (MJ/kg)	43.124
Burner Pressure Ratio	0.958
Inlet Mass Flow Rate (kg/s)	300.25
Nominal LP Spool Speed	4000
Nominal IP Spool Speed	7800
Nominal HP Spool Speed	12000
Polytropic Inner Fan Efficiency	0.8939
Polytropic Outer Fan Efficiency	0.8939
Polytropic IPC Efficiency	0.9023
Polytropic HPC Efficiency	0.8984
Isentropic HPT Efficiency	0.92
Isentropic IPT Efficiency	0.92
Isentropic LPT Efficiency	0.92

In this study, calculations were performed under steady-state conditions. Air and combustion gases are considered perfect gas. It was assumed that combustion was complete. The thermal losses of engine components are ignored. In addition, it is assumed that changes in kinetic energy, potential energy, kinetic exergy, and potential exergy within the engine are negligible. The results of this study were validated with data from Yingjan et al. [25]. As seen in Table (3) and Figure (2), this validation is in good agreement, and the validation error is less than 1%.

Table 3- Validation results

	Thrust (kN)	TSFC (g/kN.s)
Yingjun et al. [25]	71.14	26.25
Present Work	70.56	26.47
Error (%)	0.81	0.83

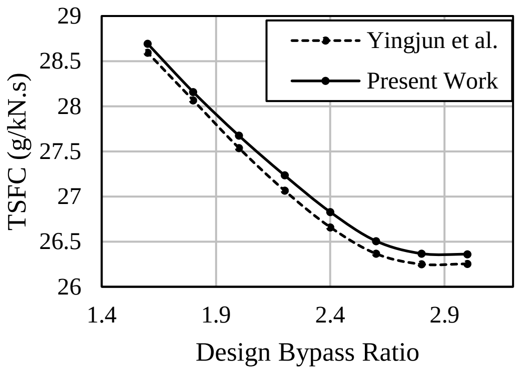

Figure 2- Comparison of the present work results with the data of Yingjan et al. [25]

Results and discussion

In this study, a three-spool mixed-flow turbofan engine is investigated. First, in the energy analysis section, the effects of the most important effective parameters were evaluated. These parameters include flight altitude, flight Mach number, High-pressure compressor pressure ratio (HPCPR), Intermediate-Pressure Compressor Pressure Ratio (IPCPR), Fan Pressure Ratio (FPR), design bypass ratio (BPR), and burner exit temperature (BET). The effects of the mentioned parameters on the turbofan performance characteristics, such as thrust and TSFC, were investigated. It should be noted that the effects of HPCPR and IPCPR are considered the effect of compression system pressure ratio (CSPR), which is equal to HPCPR multiplied by IPCPR. In the next section, exergy analysis was performed for each turbofan component to identify low-efficiency components. Subsequently, a parametric study was conducted to improve burner exergy efficiency. Finally, a sensitivity analysis was performed to identify the parameters with the most and least effect on thrust and TSFC.

Energy analysis

Parametric study of flight altitude and Mach number

First, a parametric study was performed in which two parameters, the flight Mach number and flight altitude, were considered as variables. Therefore, the Mach number range is assumed from 1.2 to 1.6 at intervals of 0.1. Then, at each of these Mach numbers, engine performance is investigated at five different altitudes from 15000 to 17000 meters at intervals of 500. Thus, 25 different cases are examined, and the engine performance is studied in each case. Figures 3, 4, and 5 demonstrate the effects of the above two parameters on thrust, TSFC, and overall energy efficiency of turbofan, respectively.

As shown in Figure 3, the thrust decreases as the flight altitude in each constant Mach number increases. This is because as the altitude increases, the ambient air density is reduced; therefore, the engine intake airflow rate is reduced.

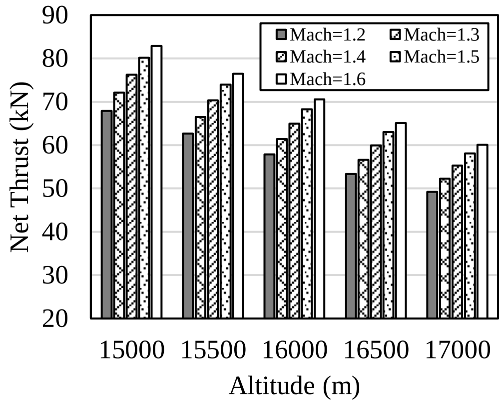

Figure 3- Effects of altitude and Mach number on thrust

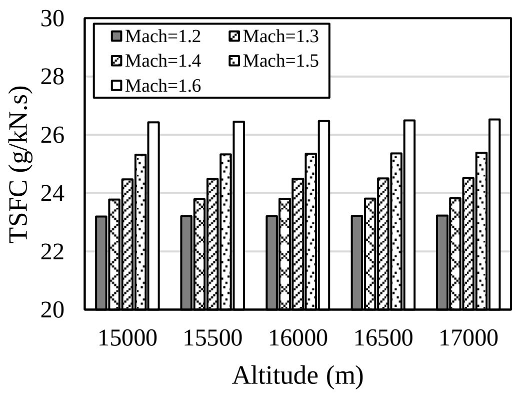

Figure 4- Effects of altitude and Mach number on TSFC

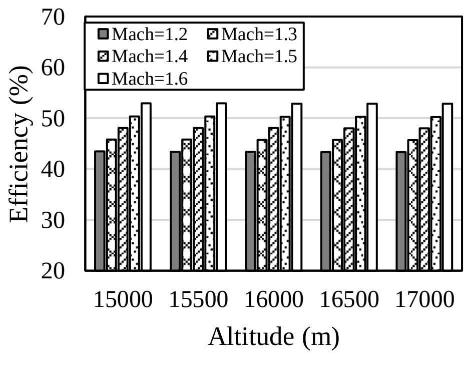

Figure 5- Effects of altitude and Mach number on engine efficiency

Owing to an increase in flight altitude, the net thrust decreased by 27.55%. In addition, because of an increase in flight Mach number, the net thrust increased by 22.02%. Figure 4 shows that at each constant altitude, as the flight Mach number increases, TSFC increases, the amount of which in the base case is 14.1%. This is because as the flight Mach number increases, the engine intake airflow rate increases. Extra heat must be generated at the burner; therefore, airflow temperature increases as much as required. The changes in TSFC owing to an increase in flight altitude are comparatively less and are at approximately 0.38% for the base case. Figure 5 demonstrates the increase in engine energy efficiency because of the increase in flight Mach number at any constant altitude.

Parametric study of FPR and BPR

In the next step, the fan pressure ratio and design bypass ratio are investigated. To this end, the FPR ranging from 2 to 4 with intervals of 0.5 is assumed. In each pressure ratio, engine performance is investigated in five different bypass ratios from 2 to 2.8 at intervals of 0.2. Figure 6 demonstrates the effect of FPR and BPR on thrust. As seen in this Figure, at each constant FPR, as the BPR increases, the thrust decreases. This is because of the reduction in engine core mass flow rate. The decrease in thrust owing to an increase in the BPR and the FPR in the base case is equal to 17.58% and 0.95%, respectively.

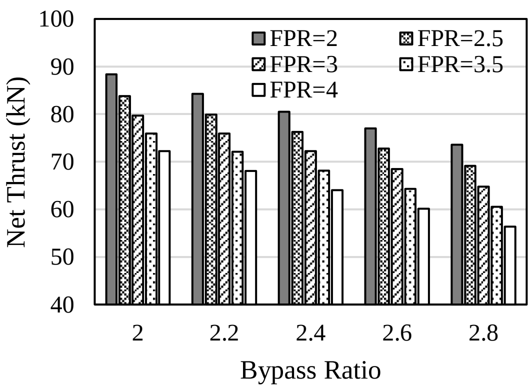

Figure 6- Effects of FPR and BPR on thrust

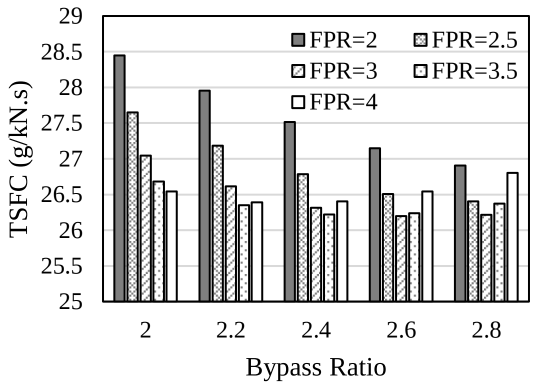

Figure 7- Effects of FPR and BPR on TSFC

Figure 7 shows the effect of FPR and BPR on TSFC and indicates that as FPR increases, the TSFC reduces owing to an increase in burner inlet air temperature, which causes less fuel to be consumed in the burner. The decrease in TSFC, owing to an increase in BPR and FPR in the base case, is equal to 4.42% and 2.2%, respectively. Figure 8 shows the increase in engine energy efficiency owing to an increase in BPR and FPR.

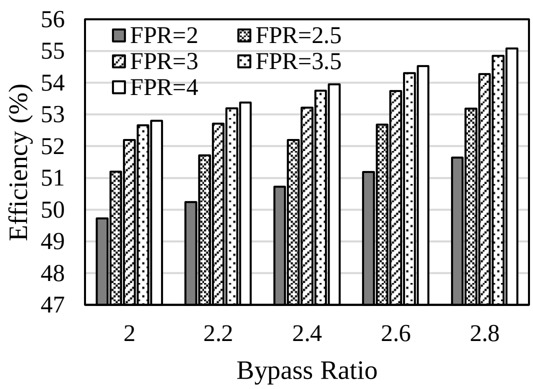

Figure 8- Effects of FPR and BPR on engine efficiency

Parametric study of CSPR and burner exit temperature

At this stage, the effects of simultaneous changes in CSPR and burner exit temperature are investigated. For this purpose, the CSPR ranging from 14.5 to 24.2 is assumed. In each of these pressure ratios, engine performance is investigated in five different burner exit temperatures from 1800 to 2000 Kelvin at intervals of 50. Figure 9 shows the effect of CSPR and BET on thrust and indicates that as the burner exit temperature increases, the thrust is also increased. Figure 10 shows the effects of CSPR and BET on TSFC. It demonstrates that TSFC increases with the increase of the BET and decreases with the decrease of the CSPR. The increases for thrust and TSFC because of the increase in the burner exit temperature are equal to 24.55% and 3.8%, respectively. Figure 11 indicates the increase in overall engine energy efficiency owing to an increase in CSPR and its slight reduction owing to an increase in burner exit temperature.

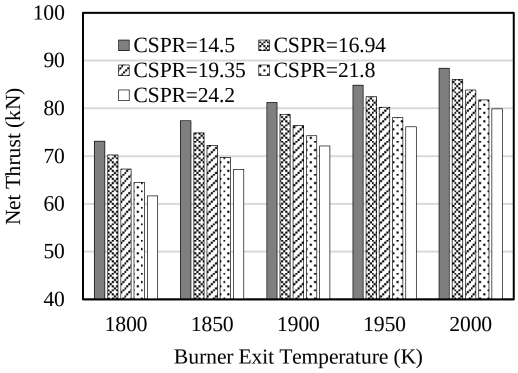

Figure 9- Effects of CSPR and burner exit temperature on thrust

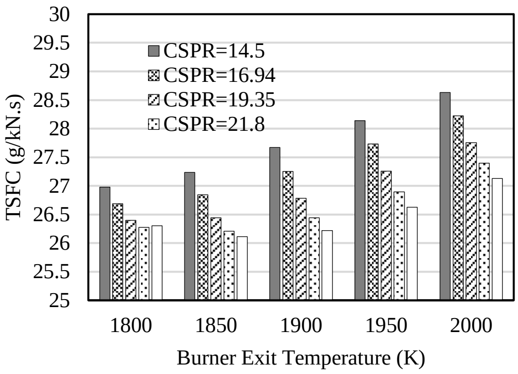

Figure 10- Effects of CSPR and burner exit temperature on TSFC

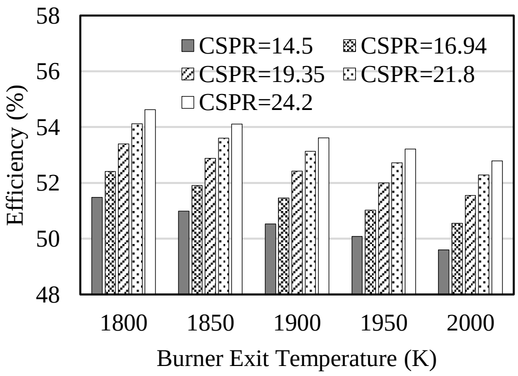

Figure 11- Effects of CSPR and burner exit temperature on engine efficiency

Exergy analysis

Figures 12-15 show the exergy efficiency, exergy destruction rate, improvement potential rate, and fuel depletion ratio for different engine components, respectively. As can be seen, the lowest exergy efficiency with a value of 85.45, the highest exergy destruction rate with a value of 22.31 Megawatts, the highest improvement potential with a value of 3.25 Megawatts, and the highest fuel depletion rate with a value of 26.67% belong to the burner.

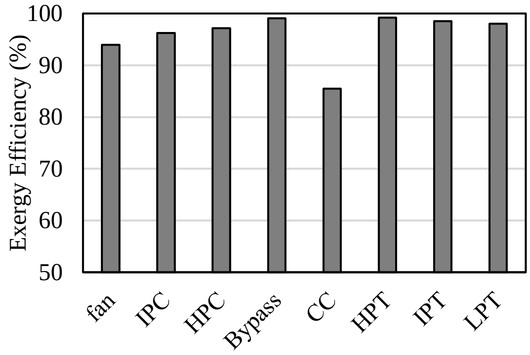

Figure 12- Exergy efficiency of turbofan engine components

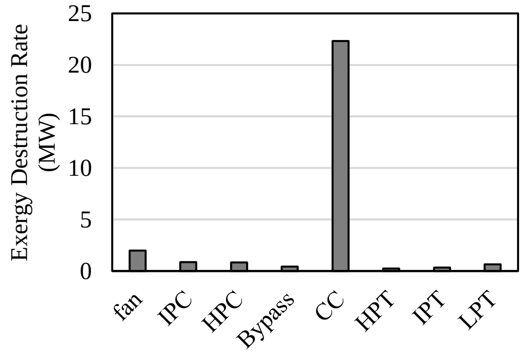

Figure 13- Exergy destruction rate of turbofan engine components

The reason for this is the irreversibility of the combustion reaction and the high-temperature difference between the burner inlet airflow and flame temperature. It can be said that the combustion chamber is the most irreversible component in the turbofan engine.

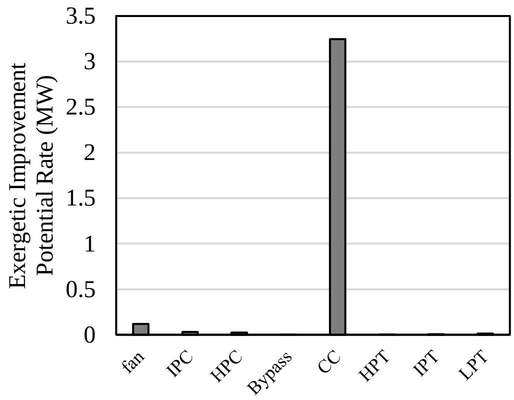

Figure 14- Improvement potential rate of turbofan engine components

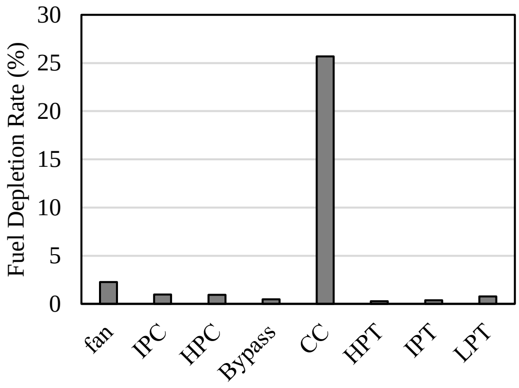

Figure 15- Fuel depletion ratio of turbofan engine components

Because the lowest exergy efficiency and the highest exergy destruction rate belong to the burner, more research is necessary regarding the combustion chamber. Therefore, the effects of different parameters on burner exergy efficiency were considered. Figure 16 demonstrates the simultaneous change effect of flight altitude and flight Mach number on burner exergy efficiency. It shows the flight altitude changes from 15000 to 17000 m and flight Mach number changes from 1.2 to 1.6. As shown in Figure 16, the burner exergy efficiency has a better result than other cases at an altitude of 15000 meters and flight Mach number of 1.6 with a value of 93.24%. It increases by 7.8% compared to the base case. Figure 17 indicates the effects of BPR and FPR on burner exergy efficiency and shows that the bypass ratio changes from 2 to 2.8 and FPR changes from 2 to 4. In the case where BPR is equal to 2.2 and FPR is equal to 2, the burner has the highest exergy efficiency with a value of 96.38%, which is increased by 12.8% compared to the base case. Figure 18 indicates the effects of CSPR and BET on burner exergy efficiency and shows the CSPR changes from 14.5 to 24.2 and BET changes from 1800K to 1950K. In the case where CSPR is equal to 24.2 and BET is equal to 1950, the burner has the highest exergy efficiency with a value of 96.38%, which is increased by 12.8% compared to the base case.

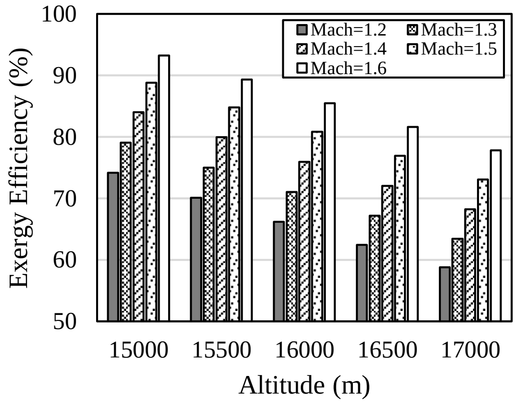

Figure 16- Effects of altitude and Mach number on burner exergy efficiency

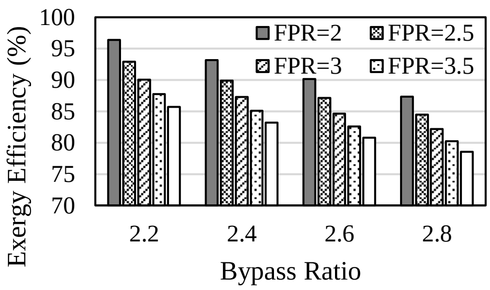

Figure 17- Effects of FPR and BPR on burner exergy efficiency

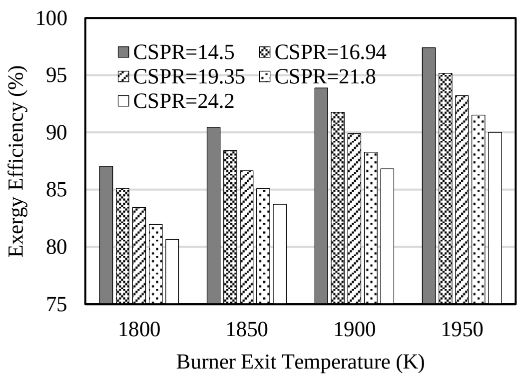

Figure 18- Effects of CSPR and burner exit temperature on burner exergy efficiency

Based on the parametric study that was performed to improve the performance of the burner, it was found that the burner has the best performance when the Altitude, Mach, CSPR, FPR, BPR, and Burner exit temperature have values of 15000m, 1.6, 14.5, 2, 2.2, 1950K, respectively. Therefore, a case was investigated under these conditions, in which the effect of improving combustion chamber performance on engine efficiency was studied, presented in Table 4.

Table 4- Effect of the improved burner on the engine efficiency

	Engine Efficiency (%)	Burner Exergy Efficiency (%)
Base Case	52.88	85.45
Improved Burner	52.94	94.80

As can be seen in Table 4, the simultaneous use of optimal parameters for burner exergy efficiency has generally increased the burner exergy efficiency by 10.94%. This strategy has increased the overall engine efficiency by 0.11%. Increasing the burner temperature along with reducing BPR to improve the burner exergy efficiency has caused an increase in TSFC. This is probably one of the main reasons for the small change in overall engine efficiency.

Sensitivity analysis

In this section, sensitivity analysis is investigated to study the influence of different input variables on engine performance parameters. This analysis determines the parameters in order of their effect on engine performance parameters such as thrust, fuel consumption, and efficiency. For this purpose, each of the parameters studied in the previous sections has been changed by 10% in the base case of the engine, and their effect on thrust and TSFC changes have been studied and compared. Figure 19 shows the results of this study. As shown in Figure 19, the burner exit temperature and HPC pressure ratio of 21.81% and 2.2 %, respectively, had the most and the least effect on the engine net thrust. Besides, the BET and the flight altitude of 4.57% and 0.11%, respectively, had the most and the least effect on the TSFC. Moreover, the flight altitude and HPCPR of 14.24% and 1.38%, respectively, had the most and the least effect on the burner exergy efficiency.

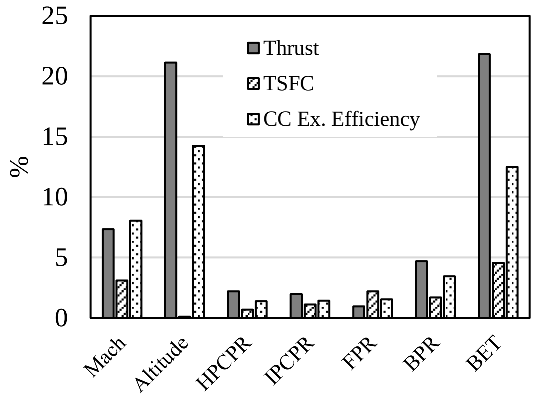

Figure 19- Percentage of thrust, TSFC, and burner exergy efficiency changes owing to a 10% change of various parameters in the engine base case

Conclusion

In this study, a three-spool mixed-flow turbofan was modeled. Moreover, the effects of some of the most important effective parameters have been investigated for energy and exergy analysis and study of engine performance characteristics, such as altitude, flight Mach number, HPC pressure ratio, bypass ratio, and burner exit temperature. exergy analysis parameters of different engine components were investigated to identify low-efficiency parts and high exergy losses. After it was found that the burner had the lowest exergy efficiency and the highest exergy destruction rate, a parametric study was conducted to improve its performance and exergy efficiency. Subsequently, the effects of different parameters on improving the burner exergy efficiency were evaluated. The results of this study are as follow:

1. Increasing the flight altitude from 15,000 to 17,000 meters reduces the thrust by 27.55%, while the TSFC changes are small.
2. Increasing the flight Mach number from 1.2 to 1.6 at a constant altitude in the base case increases the thrust by 22.02% and the TSFC by 14.1%.
3. Increasing the FPR from 2 to 4 in each constant bypass ratio reduces thrust and TSFC. For each constant FPR, increasing the bypass ratio reduces the thrust and TSFC by 17.58% and 4.42%, respectively.
4. Increasing the burner exit temperature from 1800K to 2000K in each constant CSPR increases the thrust and TSFC, equal to 24.55% and 3.8% in the base case, respectively.
5. The comparison of the effects of different parameters shows that the burner exit temperature

has the most significant effect on the turbofan engine performance and the Altitude, Mach number, Bypass Ratio, and HPCPR are in the next ranks.

6. The burner has the lowest exergy efficiency at 85.45% and the highest exergy destruction rate at 22.31 MW. The results show that the burner exergy efficiency increases by 7.8% at an altitude of 15,000 and Mach 1.6. In addition, it increases by 12.23% with a bypass ratio of 2 and an HPC pressure ratio of 3.5. When the HPC pressure ratio is 3.5, and the burner exit temperature is 2000 K, it increases by 13.2% compared to the base case.
7. In sensitivity analysis, it was found that the burner exit temperature and HPC pressure ratio of 21.81% and 2.2 %, respectively, have the most and the least effect on the engine net thrust. The BET and the flight altitude, with 4.57% and 0.11%, respectively, have the most and the least effect on the TSFC. Moreover, the flight altitude and HPCPR, with 14.24% and 1.38 %, respectively, have the most and the least effect on the burner exergy efficiency.

References

[1] Balli, O., and Hepbasli, A. “Energetic and exergetic analyses of T56 turboprop engine”, Energy Conversion and Management, Vol.6, NO.7, pp.8383-8398 (2013).

[2] Aydin, H., Turan, O., Karakoc, T. H. and Midilli, A. "Exergetic Sustainability Indicators as a Tool in Commercial Aircraft: A Case Study for a Turbofan Engine"; International Journal of Green Energy, Vol.12, pp.28–40 (2015).

[3] Sohret, Y., Dinc, A., Karakoc, T. H. "Exergy analysis of a turbofan engine for an unmanned aerial vehicle during a surveillance mission"; Energy, Vol.93, pp.716-729 (2015).

[4] Tona, C., Raviolo, P. A., Pellegrini, L. F., Junior, S. O. "Exergy and thermo-economic analysis of a turbofan engine during a typical commercial flight"; Energy, Vol.35, pp.952–959 (2010).

[5] Yadav, R., Jugseniya, C.B. and Pashilkar, A.A. “Thermodynamic Analysis of Turbofan Engine”, ASME Turbo Expo (2005).

[6] El-sayed, A. F., Emeara, M. S., El-habet, M. A., “Performance Analysis of High-Bypass Ratio Turbofan Aeroengine”, International Journal of Development Research, Vol. 35, pp. 952-959 (2010).

[7] Liew, K.H., Urip, E., and Yang, S.L., Mattingly, J.D. and Marek, C.J. “Performance Cycle Analysis of Turbofan Engine with Inter-stage Turbine Burner”, Journal of Propulsion and Power, Vol. 22, No. 2, pp. 411-416 (2006).

[8] Liu, F. and Sirignano, W.A. “Turbojet and Turbofan Engine Performance Increases Through Turbine Burners” Journal of Propulsion and Power, Vol. 17, NO. 3, pp. 695-705 (2001).

[9] Asako, T., Miyagawa, H., Miyata, S. and Kudo, K. “Conceptual Design of Aircraft Engine Using Multidisciplinary Design Optimization Technique”, ICAS 2002 Congress (2002).

[10] Atashkari, K., Nariman-Zadeh, N., Pilechi, A., Jamali, A. and Yao, X. “Thermodynamic Pareto optimization of turbojet engines using multi-objective genetic algorithms”, International Journal of Thermal Sciences, Vol. 44, pp. 1061–1071 (2005).

[11] Homifar, A., Lai, H.Y. and McCormick, E. “System optimization of turbofan engines using genetic algorithms”, Applied Mathematical Modelling, Vol. 18, pp. 72-83 (1994).

[12] Choi, J.W., Sung, H.G. “Performance Analysis of an Aircraft Gas Turbine Engine Using Particle Swarm Optimization”, International Journal of Aeronautical & Space Science, Vol.15, NO.4, PP.434-443 (2014).

[13] Turan, O. “An exergy way to quantify sustainability metrics for a high-bypass turbofan engine”; Energy, Vol.86, pp.1-15 (2015).

[14] Turan, Ö. “Mach Number Effect on The Thermodynamic Efficiencies of a Turbojet Engine: An UAV Application”, OHU Journal of Engineering Sciences, Vol. 7, NO. 2, pp. 848-863 (2018).

[15] Balli, O. “Advanced Exergy Analysis of a Turbofan Engine (TFE): Splitting Exergy Destruction into Unavoidable/Avoidable and Endogenous/ Exogenous”; International Journal of Turbo Jet Eng., aop (2017).

[16] Balli, O. “Exergy modeling for evaluating sustainability level of a high-bypass turbofan engine used on commercial aircrafts”; Applied Thermal Engineering, Vol.123, pp.138–155 (2017).

[17] Turgut, E. T., Karakoc, T. H., Hepbasli, A., Rosen, M. A. “Exergy analysis of a turbofan aircraft engine”; International Journal of Exergy, Vol.6, No.2 (2009).

[18] Yildirim, E., Altuntas, O., Mahir, N., and Karakoc, T. H. “Energy, Exergy Analysis and Sustainability Assessment of Different Engine Power for Helicopter Engines”; International Journal of Green Energy (2017).

[19] Zahedzadeh, M., Goodarzi, A., Doostdar, M. “Energy and Exergy Analysis of a Turboprop Engine in Various Operating Condition”; Energy Engineering & Management, Vol.9, No.1, pp.64-75 (2019).

[20] Dinc, A. “NOx emissions of turbofan powered unmanned aerial vehicle for complete flight cycle”, Chinese Journal of Aeronautics, Vol.33, No. 6, pp.1683-1691 (2020).

[21] Dinc, A., Elbadawy, I. “Global warming potential optimization of a turbofan powered unmanned aerial vehicle during surveillance mission”, Transportation Research Part D 85 (2020).

[22] Gorji, M., Kazemi, A. and Domiriganji, D. “Thermodynamic Study of Turbofan Engine in Off-

Design Conditions", Journal of Basic and Applied Scientific Research, Vol. 2, pp. 11239-11253 (2012).

[23] Turgut, E. T., Karakoc, T. H. and Hepbasli, A. "Exergetic analysis of an aircraft turbofan engine"; International Journal of Energy Res., Vol.31, pp.1383–1397 (2007).

[24] Li, Q., and Fan, W. "Parametric Cycle Analysis of Dual-Spool Mixed-Exhaust Turbofan with Inter-stage Turbine Burner", 45th AIAA Aerospace Sciences Meeting and Exhibit (2007).

[25] Yingjun, W., Minghao, G., Yu, H., Min, C. "CJ-3000 Turbofan Engine Design Proposal"; Beihang University.