



Energy and Exergy Analysis and Optimization of Turbofan Engine-TF30-P414

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The turbofan engines are one of the constitutes significant components of the aero engines. In this study, the thermodynamic modeling of the TF30-P414 turbofan engine is developed and validated with reference values. The aims of this research are to determine the effect of the changes in the thrust, fuel mass flow rate, and thermal efficiency with changes of the flight-altitude (H) and the flight-Mach number (Ma). Then, the changing of the exergy efficiency and exergy destruction rate were investigated. The results show that between the different components of the engine in different flight circumstances, the highest exergy destruction occurred in the combustion chamber and the lowest exergy destruction occurred in the nozzle. Also, optimization with the objective function of finding optimum flight conditions to find the highest exergetic efficiency in the flight-Mach number of 1.2 to 2.2 and the flight altitude of 10,000 to 15,000 meters. The results of this optimization reported that the maximum exergetic efficiency happened to the conditions of H=11236 meters and Ma=1.944 with an amount of 32.64%.

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NOMENCLATURE

T_3	The inlet temperature of the combustion chamber, K	η_{exc}	The exergy efficiency of the compressor
e_x	The specific chemical exergy of the fuel flow, kJ.kg^{-1}	D	The flight air density, kg.m^{-3}
E_i	The inlet exergy rate, kW	ED_c	The exergy destruction rate of the compressor, kW
W_c	The power of compressor, kW	ED_{cc}	The exergy destruction of the combustor, kW
η_{exCC}	The combustor exergy efficiency	ED_n	The nozzle exergy destruction rate, kW
r_p	The overall compression ratio	ED_T	The exergy destruction rate of the turbine, kW
b_p	Bypass ratio	E_o	The outlet exergy rate, kW
η_{istur}	Turbine inlet temperature	E_x	The chemical exergy of the fuel flow, kW
η_{iscomb}	Compressor isentropic efficiency	Ma	Flight Mach number
η_{isfan}	Fan isentropic efficiency	$P_{external}$	Pressure in the nozzle discharge, kPa
$C_{a,v}$	Specific heat capacity, J/kgK	P_o	Ambient pressure, kPa
A_{ex}	Nozzle area, m^2	Q_H	Heat transfer rate of combustion chamber, kW
A_o	The area of the input air channel to the engine, m^2	R	Global constant gas, J/kgK
V_o	Flight speed, m/s	T4	The outlet temperature of the combustion chamber, K
g_c	Gravity acceleration, m.s^{-2}	TSF	Specific thrust, g/kNs
m_a	Mass flow rate of the airflow, kg/s	$V_{external}$	Flow velocity in the nozzle discharge, m/s
m_f	Fuel mass flow rate, kg/s	WT	The turbine power, kW
η_p	The propulsive efficiency	η_{exn}	The exergy efficiency of the nozzle
η_{TH}	Thermal efficiency	FHV	Fuel heat value, MJ/kg
η_{ex}	The overall exergy efficiency	NO_x	Nitrogen oxides
η_{exT}	The exergy efficiency of the turbine		

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INTRODUCTION

The gas turbine (GT) engines are a type of thermal machine based on the Brayton cycle. Thermodynamically, they supplied heat from the fuel ignition with the air and the mechanical power or the propulsion force production. The turbojet engine is the simplest form of air gas turbine engine. At first, the air is initially concentrated in the compressor in these engines. After leaves the compressor, the air moves into the combustion chamber to react with fuel, and the supplied heat from the air and fuel combustion causes a rise in the outlet temperature of the combustor. Accordingly, the flow enthalpy is increased at the turbine entrance. For these two reasons, the turbine can be run. Hence, it discharges at the nozzle, the thrust force is generated due to the velocity and pressure at the nozzle output and output surface area [1-3].

The turbofan engines are one of the constitutes significant components of the aero engines. The turbofan engines are classified into two categories as a mixed-flow turbofan engine or an unmixed-flow turbofan engine. The unmixed flow turbofan is composed of a turbojet core, an axial fan, and a bypass flow. In this configuration, the incoming airflow passes through the axial fan before entering a core compressor, the velocity and pressure of the flow are increased. Then part of the flow of air enters the core compressor, and a portion of the flow is entering the bypass flow. The bypass flow is discharged through the cold path nozzle and the output flow from the turbine through the hot path in the environment. In the turbofan engines, the cold mixed flow, and the core flow enter into the mixer before entering the nozzle, and then, it discharged from the nozzle to the ambient [4, 5].

The thermodynamic analysis evaluated the thermal system efficiency and performance including the energy and exergy analysis. The energy analysis is related to the quantity of energy, but the economic analysis examines the energy quality. The energy is related to energy loss during a process, the production of entropy, and power loss opportunities cause by the Exergy analysis, which can determine the types, the status of location, and the proper size of the exergy losses [6-8].

Recently, Many researchers studied energy and exergy performance via parametric study and the effects of each parameter on energy and exergy efficiency [9, 10]. For instance, Alibeigi et al. [11, 12] parametrically worked on a triple cycle combination counting the gas turbine cycle (GT), reheat cycle, and an organic Rankine cycle, by coupling geothermal with a biomass energy source and solar energy source, Also, in their other study, they thermodynamically investigated the effect of organic fluids and pinch temperatures on the Rankine cycle performance by using microturbine.

Sabzehali et al. [13] studied on a new micro-GT engine. They considered the effect of inlet air cooling on

the performance of the micro gas turbine engine by changing the parameters such as the temperature difference between the inlet air temperature (IAT) based on International Society of Automation (ISA) standard and turbine inlet temperature (TIT). Subsequently, they optimized the proposed cycle based on the genetic algorithm with two separate objectives, SNO_x minimization, and thermal efficiency maximization, separately.

In another study, Vadlamudi et al. [14] simulated a simple open cycle gas turbine is modeled to carry out thermodynamic analysis with different open-loop steam cooling techniques to increase the lifespan of the turbine blade's active cooling.

Turgut et al. [15] explored the exergy analysis of the turbofan engines on the 11,000 meters from the sea level height. They also determined the exergy losses and exergy efficiency of the engine components. Coban et al. [16] inspected the application of thermodynamic rules on a military helicopter engine. The results illustrated that the highest exergy destruction values in the combustion chamber have the highest rather than the other components. Turan et al. [17, 18] considered the impact of reference heights on the exergy efficiency of a turbofan engine with a special economic aid investigation. In their works, the exergy efficiency of a turbofan is composed that at 4000 meters at the 5000 meters, it calculated as 50.3 % and 48.5 %, respectively. They have also conducted a similar study for the engine of a turboshaft engine. Similarly, Etele and Rosen [19] performed the Exergy analysis on a jet engine for flight heights of 15,000 meters of sea level. Bali et al. [20] parametrically, assessed energy and exergy performance of a GT. Rahman et al. [21] studied the parametrically the thermodynamic gas turbine (GT) performance. The efficacy of parameters such as compression ratio of the compressor, the temperature of ambient, fuel consumption ratio with air, and turbine inlet temperature on gas turbine plant performance were investigated. They found that the compressor ratio and fuel consumption ratio with air had a significant impact on the GT thermal efficiency. In another study, the effects of the inlet air temperature on the GT cycle with just adding the cooling system to increase the thermal efficiency have been done [13]. Bali et al. [22] investigated the exergo- economic analyses on an aircraft jet engine. The exergetic efficiency of the engine is calculated for 2421.5 kW output combustion production which was 34.8 %. Bali and Hepbasli [23] examined the energy and exergy analyses of the T56 engine as a turboprop engine in different performance modes of such as power, load, and rotational power of 75 % and 133 %. Also, the energy and exergy performance evaluation of the shaft and shaft power and combustion products are carried out. The results evidenced that the increase in height causes a reduction in exergy efficiency and increased energy efficiency. Balli

[24] showed for the turboprop that the potential system has a small enhancement because the exergy destruction rate is unavoidably 94 %.

Hashmi et al. [25] was performed the inlet air-cooling effects on the gas turbine cycles performance (GT) by the gas turb12 software. More while, the effect of the moisture and inlet temperature on the fuel consumption and heat efficiency and the heat efficiency of the turbine in this study show that by reducing the temperature of inlet air to the cycle, thermal efficiency cycle and the output power increased and the fuel consumption cycle decreased. Also, Santos and Andrade [26] have studied the effect of air temperature on the performance of a gas turbine cycle studied by increasing the temperature of the thermal efficiency and the output power of the gas turbine cycle.

Nowadays, extensive research conducted on the designers of different fields such as structure design, aerodynamic designer, etc. With regards to the importance of the aircraft engine as a landslide, the design subject of engine design is one of the most important points of design, and the engine designers always seek to improve the propulsion system. The off-design performance and dynamic back of a single heavy-duty shaft in a gas turbine plant based on a nonlinear mathematical model [27, 28].

Adolfo et al. [29] infer in thermodynamic analysis that an aircraft engine is used to assess the performance of the turbofan engine in GE90 - 94 B. They found that the emissivity of nitrogen oxides (NO_x) was 30831 g and fuel consumption of 1124 kg. Seyam et al. [30] presented the energy and exergy analysis of two industrialized high bypass three-shaft turbofan engines combined molten carbonate fuel cell (MCFC-turbofan) and solid oxide fuel cell (SOFC-Turbofan). Their consequences showed that the base turbofan had the 153 kN maximum thrust force, simultaneously, the SOFC-turbofan and MCFC-turbofan had 116 and 107 kN, respectively. The energy and exergy performance of SOFC and MCFC were meaningfully augmented compared to the ground state.

In recent years, Biodiesels are intended as an alternative to fossil fuels because of increasing the pollution of the fossil fuels derived from crude oil. For example, Gupta et al. [31] studied a gas turbine for power generation problems and their environmental concerns. They analyzed the soya bio-diesel production process i.e. trans-esterification, also, investigated the different physical and chemical properties of soya bio-diesel and compared to establish the suitability of the bio-diesel in the gas turbine.

In recent years extensive research has been conducted for aero-engine with different fuels to choose the beneficial performance and environment selection for example choosing the liquefied hydrogen fuel has high performance energy for using in a turbofan. Also, by considering the 1st and 2nd laws of thermodynamics, the waste exergy ratio by the index of the low bypass turbofan

engine was calculated [32-34].

Khan et al. [35] applied HAM algorithm for optimal obtained solution in couple stress fluid of a Poiseuille flow for choosing the best expression parameters.

Currently, engineers in different fields such as structure design, aerodynamic design, etc., have done so much in past decade, given the importance of the aircraft engine as a propulsion system, the engine design is one of the most important steps of design, making the engine designers always seek to improve the propulsion efficiency, thermal efficiency, thrust force, and specific fuel consumption. In this study, the dimensionless analysis of the TF30 - P414 engine mixed flow turbofan by using GASTURB software [36] based on off-design were investigated including the changes of energy and exergy efficiency of different components of the TF30-P414 engine with the Mach number and flight altitude were investigated. Also, the cause of the cycle's irreversibility, the destructive exergy calculated in a different component. Correspondingly, the Mach number affects the mass fuel flow rate, and thrust force were investigated. Eventually, the overall efficiency is maximized regarding the optimization by the genetic algorithm.

THERMODYNAMIC MODELING OF THE TURBOFAN CYCLE

The TF30-P414 engine cycle is assumed as a mixed-flow turbofan engine cycle. It is a twin-spool mixed-flow turbofan engine with a high-pressure spool involving the high-pressure turbine (HPT) connected with the high-pressure compressor (HPC), which has mixed with a low-pressure spool involving the low-pressure turbine (LPT) before nozzle with the fan and the low-pressure compressor (LPC) [37]. The turbofan prototypical schematic is presented in Figure 1.

The temperature and pressure of the inlet air play an important role in the temperature and pressure of other parts of the cycle. Also, the real inlet mass flow rate is the function of the velocity and density of the input air. Since

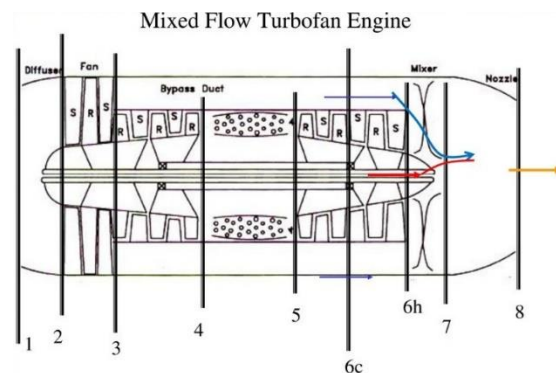


Figure 1. The mixed-flow turbofan Engine modeling

the pressure and temperature are the functions of the flight height, the inlet flow velocity is the function of the flight-Mach number. The relative equation has delivered in the following equations. The real air inlet mass flow rate is obtained from Equation (1).

$$m_a = DV_0A_0 \tag{1}$$

The additive heat transfer rate to the combustion chamber is evaluated in the following equation;

$$Q_H = m_a C_{av} (T_4 - T_3) \tag{2}$$

The fuel mass flow rate is equal to the heat ratio of the thermal value per kilogram of fuel and is obtained from Equation (3).

$$m_f = \frac{Q_H}{FHV} \tag{3}$$

The thrust force in a mixed flow turbofan engine is calculated as follows:

$$Thrust = m_a (V_{ex} - V_0) + A_{ex} (P_{ex} - P_0) \tag{4}$$

The thrust specific fuel consumption (TSFC) is obtained from Equation (5).

$$TSFC = \frac{m_f}{Thrust} \tag{5}$$

The thermal efficiency is estimated by Equation (6).

$$\eta_{TH} = \frac{m_a (V_{external}^2 - V_0^2)}{2Q_H} \tag{6}$$

The Propulsive efficiency is the thrust product over the flight speed to the difference of the kinetic energy during the engine and is extracted from Equation (7).

$$\eta_p = \frac{2 \cdot Thrust}{m_a (V_{ex}^2 - V_0^2)} V_0 \tag{7}$$

The chemical Exergy of the fuel flow is calculated.

$$m_f e_x Ex = m_f e_x \tag{8}$$

The overall efficiency is considered as the multiplied of the propulsive efficiency to thermal efficiency.

$$\eta_{Overall} = \eta_p \cdot \eta_{TH} \tag{9}$$

It should be noticed that the ex for JP10, which is equal to 44927 kJ/kg [8]. The overall thermal efficiency of the turbofan engine is the flight velocity fraction crossed to the thrust force to the chemical exergy of the inlet fuel consumption flow of the engine. The relationships related to the exergy analysis of the cycle components are tabulated in Table 1. Table 2 presents the input data of the TF30 - P414 engine cycle.

The performance results of the TF30 - P414 engine is displayed compared to the reported values [38] in Table 3. The consequences indicate that it has a good agreement for continuing the calculation.

Table 1. Exergy analysis of cycle components

Component	Exergy efficiency	Destruction rate of exergy
Compressor	$\eta_{exc} = \frac{E_0 - E_i}{W_c}$	$E_{DC} = W_c - (E_0 - E_i)$
Turbine	$\eta_{ext} = \frac{W_T}{E_i - E_o}$	$E_{DT} = E_i - E_o - W_T$
Combustion chamber (CC)	$\eta_{exCC} = \frac{E_o}{E_i - E_f}$	$E_{Dcc} = E_i - E_o + E_f$
Nozzle	$\eta_{exn} = \frac{E_o}{E_i}$	$E_{Dn} = E_i - E_o$
Overall Exergy	$\eta_{ex} = \frac{FV_o}{Ex}$	$EX = E_{Dn} + E_{Dcc} + E_{DT} + E_{DC}$

Table 2. The input parameters of the TF30 - P414 engine

Parameters	Amounts	Units
r_p	19.80	-
b_p	0.878	-
TIT	1449	K
m_a	101.787	Kg/s
η_{isTur}	0.91	-
FHV	42.076	MJ/Kg
η_{iscomb}	0.86	-
η_{isfan}	0.88	-

Table 3. The performance results of the TF30 - P414 engine compared to reference values

	Thrust (kN)	TSFC (g/kNs)
Reference value	56.937 [38]	25 [27]
Present study	58.80	23.924
Deviation (%)	-3.16	-4.30

RESULTS AND DISCUSSION

Parametric thermal study

The real airflow of the engine on flight Mach is given in Figure 2a. At any constant altitude, the Mach number increasing and the rapidly speed increases with the velocity increases, the real flow rate of the incoming air to the engine increases. Also, increasing the altitude in a constant Mach due to the decrease in the ambient air density according to the Equation (1), the real input airflow decreases. The power of the thrust force is

represented in terms of flight-Mach number and flight altitude in Figure 2b. Increasing the flight-Mach number in the constant flight height increases the real input air mass flow to the engine, and according to Equation (4), the engine thrust force also increases, on each Mach number, the flight height, the real flow of the input air should be reduced, as well the engine thrust force reduces. The variation of the fuel flow is shown in Figure 2c. At any constant height with the augmenting flight Mach number, the real air mass flow rate flow of the incoming airflow to the engine increases, so the required heat transfer rate Q_H is increased where the inlet and outlet combustion chamber temperatures are required. Accordingly, the heat value per fuel is increased when the Q_H is constant. The real air mass flow rate to the engine lessens with the constant flight Mach number and decreasing of the flight altitude, so it requires less heat to deliver the incoming air into the combustion chamber to

the temperature of the turbine. So, the heating rate is decreased and the consumption of fuel is reduced in exchange of the constant heat value for the fuel mass flow rate. Variations of specific fuel consumption in terms of altitude and Mach number are presented in Figure 2d. By increasing the Mach number at any constant height, the intensity increased the fuel consumption which is higher than the intensity of increasing the thrust force, so the motor fuel consumption has increased.

The variation of thermal efficiency and change of propulsive efficiency in terms of the height and Ma are shown in Figure 3.

Parametric exergy analysis

In this study, the effect of flight-Mach number, flight altitude on the overall exergy efficiency and fuel flow consumption of the TF30P414 engine were investigated. Also, the efficacy of Ma at the constant flight height of

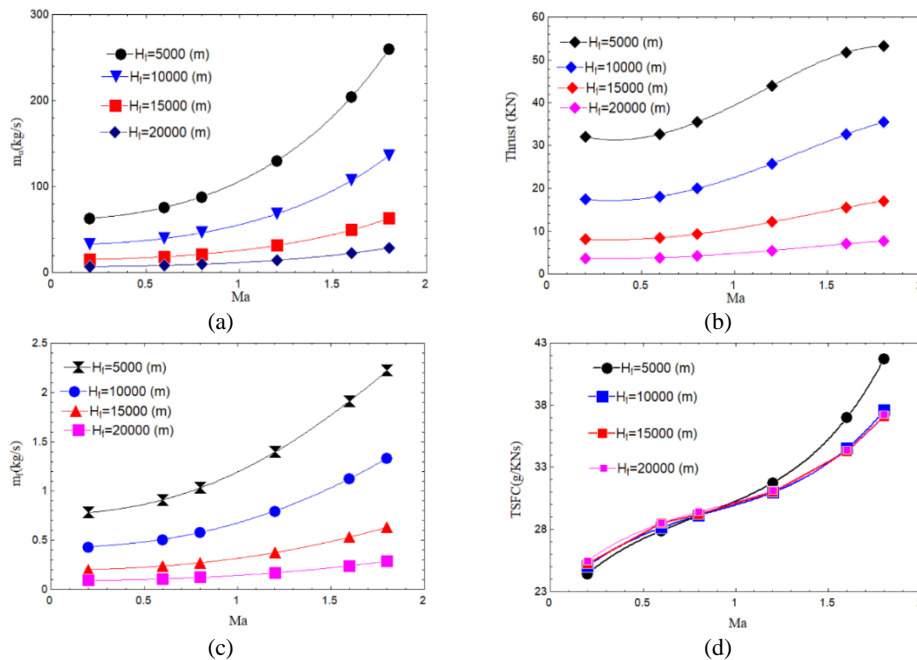


Figure 2. The flight-Mach number efficacy on (a) the real-air flow of the engine, (b) the thrust force, (c) the fuel mass flow rate and (d) the TSFC

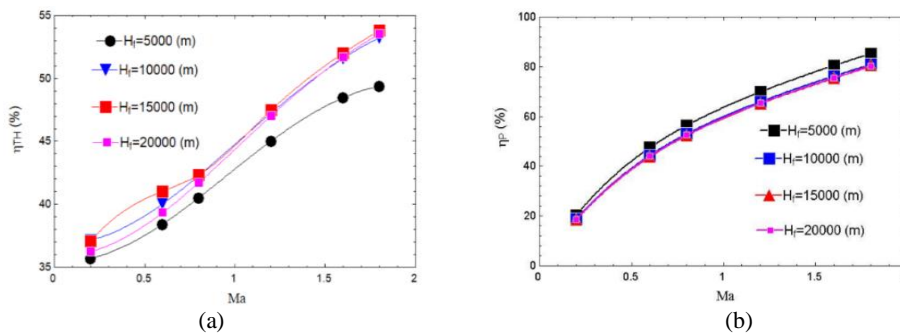


Figure 3. Variation of (a) thermal efficiency, and (b) the change of propulsive efficiency in terms of the height and Ma

10,000 m on the exergetic efficiency and exergy losses of the parts of the proposed cycle is examined. The thermodynamic properties of the flow at different components of the engine per flight Mach number variation at a constant altitude of 10,000 m are represented in Tables 3-6, respectively.

The performance changes of the TF30 engine components with flight - Mach are represented at an altitude of 10, 000 m in Figure 4. Furthermore, the flight Mach number rises the exergy efficiency of the peak pressure compressor and the combustion chamber and it has an exergy efficiency near 100%. Also, the exergy efficiency of HPT, LPC, and HPC is in the range of 80 and 98.69 % on the different flight Mach numbers. The exergy efficiency of the combustion chamber at different flight Mach numbers has a value ranging between 75 and 80 %. The variation of the exergy destruction rate (E.D.) of the TF30 engine components with flight Mach number at a constant height of 10,000 meters is shown in Figure 5. The results showed that the E.D. rate in the combustion chamber was much higher than the other components. The E.D. rate at the nozzle is also very low and close to zero. In addition, with different flight Mach numbers, the

Table 3. The flow characteristics of the different parts of the engine are at a height of 10, 000 m and Ma = 0.8

Flow stations	\dot{M} (kg/s)	T (K)	P (kPa)	h (J/kg)	e (J/kg)
HPC inlet	24.63	239.76	33.638	-46528	28074.2
Combustor inlet	24.63	499.36	359.151	208143	28070.066
HPT inlet	25.325	1430.1	337.969	1330000	1330000
LPT inlet	25.325	1218.82	159.834	1072000	852382
Mixer inlet	25.325	1192.93	143.516	556843	410942
Nozzle inlet	46.95	816.36	92.76	556843	410942
Nozzle outlet	46.95	699.733	51.033	556843	410942

Table 4. The flow characteristics of the different parts of the engine are at a height of 10,000 m and Mach 1.2

Flow stations	\dot{M} (kg/s)	T (K)	P (kPa)	h (J/kg)	e (J/kg)
HPC inlet	36.357	237.84	53.068	-10631.1	63422.4
Combustor inlet	36.357	567.73	566.67	279760	340062
HPT inlet	37.315	1430.2	533.13	1319000	1133000
LPT inlet	37.315	1119.69	266.015	1034000	843108
Mixer inlet	37.315	1115.21	196.65	967948	775964
Nozzle inlet	69.237	812.59	142.99	551982	435153
Nozzle outlet	69.237	696.144	78.65	551982	435153

Table 5. The flow characteristics of the different parts of the engine are at a height of 10km and Ma = 1.6

Flow stations	\dot{M} (kg/s)	T (K)	P (kPa)	h (J/kg)	e (J/kg)
HPC inlet	57.101	321.45	90.309	39626.3	111772
Combustor inlet	57.101	661.5	964.28	379398	437792
HPT inlet	58.456	1429.50	906.982	1315000	1163000
LPT inlet	58.456	1148.64	328.85	980182	823725
Mixer inlet	58.456	1104.84	272.939	902557	744698
Nozzle inlet	108.591	807.58	233.90	545512	462033
Nozzle outlet	108.591	691.384	128.605	545512	462032

Table 6. The flow characteristics of the different parts of the engine are at a height of 10km and Ma = 1.8

Flow stations	\dot{M} (kg/s)	T (K)	P (kPa)	h (J/kg)	e (J/kg)
HPC inlet	72.579	350.28	119.844	70138.4	141084
Combustor inlet	72.579	717.27	1279.59	439501	496694
HPT inlet	74.186	1428.87	385.42	1312000	1180000
LPT inlet	74.186	1123.79	396.046	947795	809687
Mixer inlet	74.186	1073.3	318.825	863155	723475
Nozzle inlet	137.911	804.724	300.394	541800	475414
Nozzle outlet	137.911	688.656	165.128	541800	475413

E.D. of the HPC is greater than the E.D. rate at HPT and the LPT E.D. rate is lower than the HPT E.D. rate. The exergy changes of the TF30 engine fuel flow with the flight-Mach number were represented at a constant flight height of 10,000 meters in the form of the JP10 fuel in Figure 6. Since the flow rate of fuel increases with increasing the Mach number at a constant height of 10,000 meters, according to Equation (8), the chemical exergy of fuel flow increases with increasing the flight Mach number. Exergy fuel flow changes of the TF30 engine with a flight height at Mach number 2 constant per JP10 fuel are shown in Figure 6.

The exergy rate of the incoming fuel flow reduced because of the reduction in the mass flow rate of the fuel by increasing the flight altitude at constant flight Mach number.

The performance changes of the TF30 engine components with flight - Mach at an altitude of 10,000 m are represented in Figure 4. Furthermore, the exergy efficiency reaches nearly to 100% when the flight Mach number rises the exergy efficiency of the compressor peak pressure and the combustion chamber increases. Also, the exergy efficiency of HPT, LPC, and HPC is in the range of 80 and 98.69 % at different flight Mach

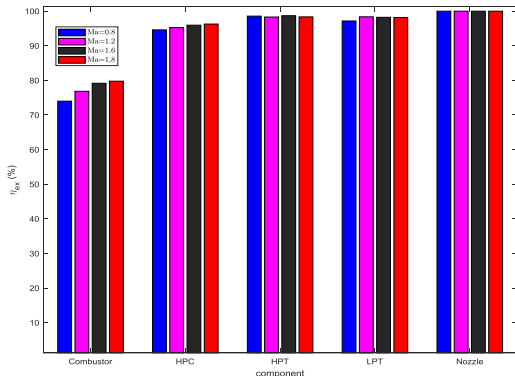


Figure 4. The changes in the η_{ex} of the TF30 engine parts with Ma at a constant height of 10,000 meters

numbers. The exergy efficiency of the combustion chamber at different flight Mach numbers has a value ranging between 75 and 80 %. The variation of the exergy destruction rate (E.D.) of the TF30 engine components with flight Mach number at a constant height of 10,000 meters is shown in Figures 5. The results showed that the E.D. rate in the combustion chamber was much higher than the other components. The E.D. rate at the nozzle is also very low and close to zero. In addition, at different flight Mach numbers, the E.D. of the HPC is greater than the E.D. rate at HPT and the LPT E.D. rate is lower than

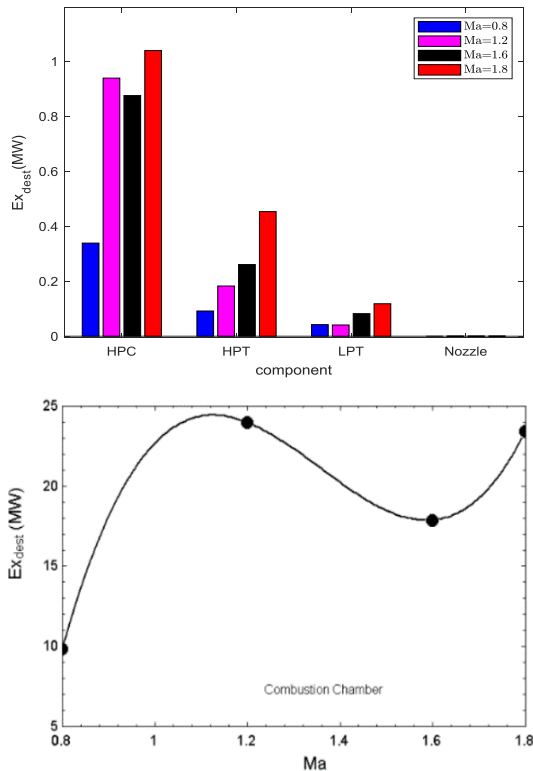


Figure 5. The deviations in the E.D. rate of the TF30 engine parts with flight - Mach number at a constant height of 10,000 meters

the HPT E.D. rate. The exergy changes of the TF30 engine fuel flow with the flight-Mach number at a constant flight height of 10,000 meters in the form of the JP10 fuel are represented in Figure 6. Since the flow rate of fuel increases with an increase in the Mach number at a constant height of 10,000 meters, according to Equation (8), the chemical exergy of fuel flow increases with an increase in the flight Mach number. Exergy fuel flow changes of the TF30 engine with a flight height at Mach number 2 constant per JP10 fuel are shown in Figure 6. Since an increase in the flight altitude with each constant flight Mach number reduces the fuel mass flow rate, the efficacy of the flight Mach number reduces the Exergy rate of the incoming fuel flow.

The exergy efficiency changes with the Mach number at a constant flight height of 10,000 meters in the form of JP10 fuel are represented in Figure 6. By increasing the Mach number, the thrust force and flight speed are increased at a constant height of 10,000 meters and the intensity of increasing the cross of the flight speed and thrust force is higher than the intensity of the increase in the energy rate of the fuel flow; thus, increasing the Mach number at a flight height of 10,000 meters, the exergy efficiency of the TF30 engine increases.

The η_{ex} of the TF30 engine with flight Mach number of constant two for the JP10 fuel is illustrated in Figure 6. The findings show the highest and lowest exergy efficiency of the TF30 engine is at Ma = 2 and H = 10 km, and Ma = 2 and H = 20 km, respectively.

Optimization

Teaching-learning-based optimization (TLBO) is derived from the teaching and learning process. It is based on the influence of the teacher on the students' efficiency in a class. TLBO was performed during two-approach steps. The input parameters of the algorithm are the lower and upper bounds of the variables, the amount of production, and the fitness function. TLBO is considered

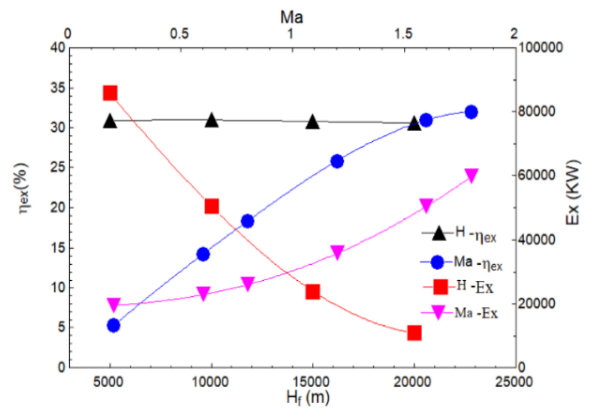


Figure 6. The changes of the exergy flow and exergy efficiency with the variation of flight altitude at Mach 2 constant and flight Mach number at a constant altitude of 10,000 meters per JP10 fuel

to be the basis of the optimization approach. First, the members of the class are generated for the Variables boundary. The best response is chosen according to the fitness function of the instructor [39].

Instructor phase

The first stage is called the training phase, the instructor tries to influence the level of knowledge of the members. The class raised its mean to increase the ability of the class. This random process depends on many aspects. The parameters at any interaction (i), M_i and T_i are the mean level of class and Teacher at any iteration. T_i will be near to the M_i after teaching development and it is named M_{new} . So, The difference and the mean of these two parameters subtract from each other. This subtraction is defined as follows:

$$difference - mean_i = r_i (M_{new} - T_i M_i) \tag{18}$$

where, r_i is a random number in the range of 0 to 1 and T_F is the educational factor which can be determined the education quality and Master's ability to transfer knowledge.

Learner phase

At this stage, the population (who are a classmate) develops their knowledge by working together. One of the most important features of this algorithm is the lack of dependence on the parameters. Because the algorithm has the lowest possible number of parameters and hence, it can have a particular advantage. The acquaintance of learners improves with input teacher feedback and also among of their interaction. Arbitrarily, the learners cooperate with other learners in a group to learn or discuss the project, the presentation, etc. so it can help interactively and they exchange the information together [39, 40]. Learner modification is articulated as:

For $i=1:P_n$

Arbitrarily, choose two learners X_i and X_j , where $i \neq j$

If $f(X_i) < f(X_j)$

$$X_{new,i} = X_{old,i} + r_1 (X_j - X_i)$$

Else

$$X_{new,i} = X_{old,i} + r_1 (X_i - X_j)$$

End If

End For

Accept X_{new} if it gives a better function value.

If the fitness function improved, this effect would be accepted. The above process is repeated until the optimal response or estimation of stopped conditions. The flowchart of the TLBO approach is shown in Figure 7.

In this section, the TF30-P414 turbofan engine is optimized. The optimization approach is produced by the TLBO algorithm with the objective function such as TIT, bypass ratio, and the flight altitude with the JP10 as a fuel. The range of bypass ratio is 0.4-0.9, TIT is 1400-1600 (K), flight-Mach number is 1.2-2, and flight altitude is in the range of 10000-15000 meters.

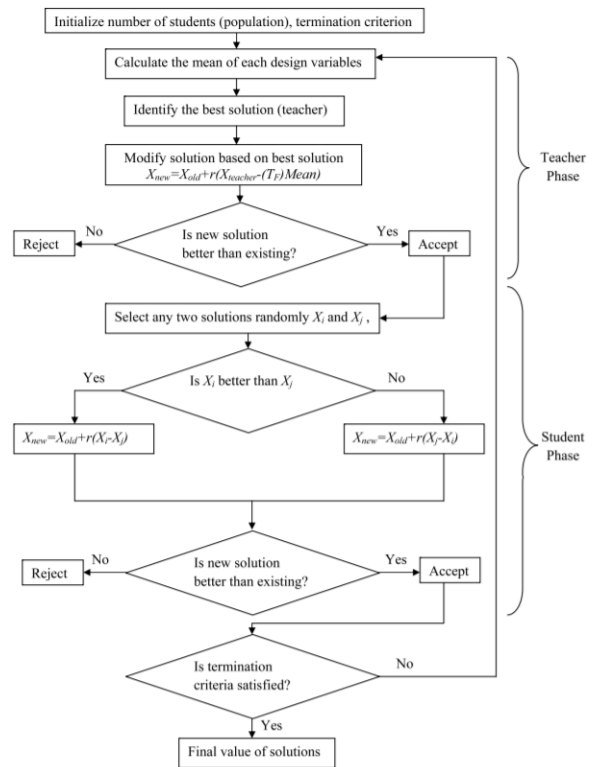


Figure 7. TLBO flowchart [41]

The optimization design variables are shown in Table 7. TSFC and thrust are the design constraints of optimization. The low and high values of TSFC are 10 and 40 g/kNs respectively, also the low and high values of thrust are 25 and 30 kN respectively. The values of the design constraints are shown in Table 8.

Subsequently, the amounts of optimized design variables are indicated in Table 9. Also, the amounts of design constraints are thrust=29.4 kN and TSFC=39.9 (g/kNs). Finally, the amount of optimized performance of the TF30-P414 engine is $m_a = 1.176$ (kg/s), $\eta_{Th} = 54.08\%$, $\eta_P = 84.4\%$, $\eta_{Overall} = 45.66\%$, and $\eta_{ex} = 32.64\%$.

TABLE 7. The optimization design variables

Parameters	Low values	High values
Bypass ratio	0.4	0.9
TIT (K)	1400	1600
Flight-Mach number	1.2	2
Flight altitude (m)	10000	15000

TABLE 8. The design constraints

Parameters	Low values	High values
TSFC (g/kNs)	10	40
Thrust (kN)	25	30

TABLE 9. The parameters of the optimized cycle

Parameters	Values
Bypass ratio	0.899
TIT (K)	1400
Flight-Mach number	1.944
Flight altitude (m)	11.236

CONCLUSION

In this paper, the TF30-P414 turbofan engine is thermodynamically investigated. At first, it has been validated with the datasheet of the TF30-P414 turbofan engine. Then, the effect of the changes in the thrust fuel consumption, mass flow rate, and thermal efficiency with the flight altitude and the flight Mach number changes were investigated. Furthermore, the exergy efficiency and destruction rate of exergy were inspected with flight - Mach number and flight altitude in each component. Finally, for finding the best condition of flight altitude and flight-Mach number, optimization has been operated. The results are reported as follows:

1. As a result of the thrust force and consumed-fuel flow rate, as well as the fuel consumption and the engine thrust, the real air inlet flow rate, grows if the Flight-Mach number increases at the constant flight altitude.
2. Increasing the flight altitude by the constant Flight – Mach number, the real flow of air to the engine is reduced due to the reduction in the air density, so the engine thrust force is reduced. Also, the consumed flow rate of fuel is reduced.
3. At any constant flight altitude, the chemical exergy rate increases due to the increase in the thrust-specific fuel consumption (TSFC). However, the increasing intensity of the thrust force and flight velocity is more than the intensity of the chemical exergy rate of fuel flow in return for increasing the Mach number, consequently, the engine exergy efficiency is increased by increasing the Mach number at constant flight altitude.
4. An Optimization has been done to find the optimized Mach number and flight altitude for the exergy efficiency maximization in the range of 1.2 to 2 and 10,000 m to 15,000 m respectively by using a single-purpose optimization algorithm named as teaching–learning-based optimization method (TLBO). The findings indicate that the uppermost exergy efficiency happened in the flight altitude of 11236 m and the Mach number of 1.994. The maximum exergy efficiency was calculated at 32.64%.

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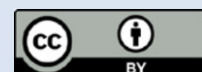
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Persian Abstract

چکیده

در این مطالعه ابتدا اقدام به مدلسازی ترمودینامیکی موتور توربو فن ۴۱۴ TF30 و اعتبارسنجی مقادیر آن با مقادیر مرجع پرداخته شد. سپس تاثیر تغییرات تراست، دبی سوخت مصرفی، مصرف مخصوص سوخت و راندمان های حرارتی و رانشی با تغییرات ارتفاع و ماک پروازی مورد بررسی قرار گرفت. پس از آن به بررسی تغییرات راندمان اگزورژی و نرخ تخریب اگزورژی با تغییرات ماک و ارتفاع پروازی پرداخته شد. در این مطالعه مشاهده شد با افزایش عدد ماک در هر ارتفاع ثابت تراست، دبی سوخت مصرفی، راندمان حرارتی و راندمان اگزورژیتیک افزایش می یابد. همچنین نتایج حاکی از آن است که از بین اجزای مختلف موتور در وضعیت های پروازی مختلف بیشترین تخریب اگزورژی در محفظه احتراق و کمترین تخریب اگزورژی در نازل اتفاق می افتد و کمترین و بیشترین نرخ تخریب اگزورژی کلی موتور در ارتفاع پروازی ۱۰۰۰۰ متری به ترتیب در ماک پروازی ۰/۸ و ۱/۲ اتفاق می افتد. بهینه سازی با هدف یافتن شرایط پروازی بهینه با تابع هدف بیشینه نمودن راندمان اگزورژی کلی موتور در محدوده ماک پروازی ۱/۲ تا ۲/۲ و ارتفاع پروازی ۱۰۰۰۰ تا ۱۵۰۰۰ متری انجام شد. نتایج این بهینه سازی حاکی از آن است که بیشترین راندمان اگزورژی کلی موتور در ارتفاع پروازی ۱۱۲۳۶ متری و ماک پروازی ۱/۹۴۴ می باشد که مقدار آن ۳۲/۶۴ درصد است.
