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Araştırma / Research

MACH NUMBER EFFECT ON THE THERMODYNAMIC EFFICIENCIES OF A TURBOJET ENGINE: AN UAV APPLICATION

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ABSTRACT

Air vehicles have evolved into extremely complex systems that need detail analysis and tools for an efficient design process. A theoretical formulation based on law of thermodynamics is proposed for assessing the propulsive performance of future aircraft configurations. It consists of the combination of a momentum balance and a fluid flow analysis involving the first and second laws of thermodynamics. To meet this need, this study presents and evaluates flight Mach number (M_0) effects on energetic and exergetic performance of a small turbojet engine. Energy and exergy analysis are applied to a small turbojet engine to examine the effects of using different aircraft velocities at constant reference environment (flying altitude is assumed to be constant at 8,000 m). The results of analysis using $0.3\leq M_0\leq 0.8$ are the exergetic and energetic efficiency ranging from 48.61% to 49.88% and 3.25% to 9.96%, respectively. Furthermore, exergy efficiency values were found to be 89.45% for the centrifugal compressor, 61.11 % for the combustion chamber and 89.21% for the turbine, and 84.15% for the exhaust, while engine exergy destruction is also slight decrease with flight Mach number.

Keywords: Turbojet, exergy, energy, UAV, IHA

MACH SAYISININ TURBOJET MOTORU TERMODİNAMİK VERİMLERİ ÜZERİNDEKİ ETKİSİ: BİR UAV UYGULAMASI

ÖZ

Hava araçlarının karmaşık yapılı sistemler olup tasarım süreçleri detaylı analizlere ihtiyaç duyarlar. Sonraki nesil uçaklarda itki sistemlerinin performansı için termodinamiği kurallarını kullanmak gereklidir. Bu sebeple termodinamiğin I. ve II. Kanunlarını, akışa ve momentum dengesine uygulamak gereklidir. Bu çalışmada, küçük bir turbojet motorunun enerji ve ekserji performansı üzerinde uçuş Mach sayısının etkileri, uçuş irtifası 8,000 m alınarak incelenmiştir. $0.3\leq M_0\leq 0.8$ aralığında motorun ekserji verimi %48.61-49.88, enerji verimi %3.25-9.96, olarak hesaplanmıştır. Bu ana verimlere ilave olarak, kompresör ekserji verimi %89.45, yanma odası ekserji verimi %61.11, türbin ekserji verimi %89.21 ve egzoz ekserji verimi 84.15 olarak hesap edilmiş olup, uçuş Mach sayının arttıkça ekserji yıkımının da düşük miktarda azaldığı görülmüştür.

Anahtar Kelimeler: Turbojet, ekserji, enerji, UAV, IHA

1. INTRODUCTION

Unmanned air vehicles (UAVs) are among the many types of aircraft. UAVs have been in service for a couple of decades in both commercial and military area. They include all classes of airplanes, helicopters, airships, and translational lift aircraft that have no onboard pilot. Design of a UAV systems are complex, similar to regular

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military or commercial aircraft. UAVs are characterized by medium or long range and/or endurance, medium to high altitude, medium to high subsonic speeds, and sensor and communication payloads [1-3].
Aircraft conceptual design tools need a propulsion model. In other words, aircraft designers need a data set of an existing engine or a detailed engine model for propulsion calculations. Better propulsion models increase the accuracy of this kind of tools. Propulsion models can be created by employing engine thermodynamic cycle analysis. Turbomachinery is candidate propulsion and power systems for Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance (UAV) and Auxiliary Power Systems (APU) for aircrafts [4]. During recent years, interest on small-sized gas-turbine engines (SSGT) has increased for both ground-based and aircraft uses. SSGT, in particular, are becoming attractive for their potential application on remote-control airplanes or on unmanned aerial vehicles (UAVs) because of their extremely-high thrust-to-weight ratio.

The performance of a turbojet engine has increased through by engine efficiency and improved material properties. A number of works exist to define optimum engine parameters for minimizing specific fuel consumption. Guha [5,6] investigates gas turbine cycle optimization including real gas effects. Energy and exergy methods are important to gain a deeper understanding of fuel efficiency of an aero vehicle and its power systems. So, energy and exergy analyses have been applied to some aircraft systems in the last 10–15 years [7-12].

The main goals of this study are:

- Evaluating flight Mach number effect on energy and exergy analysis of a small turbojet engine. It consists of an inlet, a centrifugal compressor, reverse flow combustion chamber, axial-flow turbine and exhaust nozzle. It also uses JP-8 aviation fuel.
- Calculating exergy and energy (overall) efficiencies and exergy losses/destructions, relative exergy destruction ratio, fuel depletion ratio, productivity lack, exergetic factor and improvement potential rates for turbojet engine components for different flight Mach numbers.
- Determinate energetic and exergetic performance of the turbojet engine, a computer code was developed in MATLAB program language.

Through a literature review, it is noticed that any studies on the flight velocity effect on energetic and exergetic parameters of a UAVs engine by a computer modeling have not appeared to the best of the authors' knowledge. So, the results in this study provides the first attempt to show the flight velocity of the UAVs by using MATLAB environment in modeling the energy and exergy efficiencies of a UAVs aircraft by taking into account flight Mach number characteristics. Lack of these makes this study original and becomes main motivation for UAVs aircrafts during various flight Mach numbers.

2. SYSTEM DESCRIPTION, MATERIALS AND METHOD

2.1. System Description

Turbojet engine (shown in Figure 1) for use air as the working fluid and provide thrust force based on the variation the kinetic energy of burnt gases after combustion. The study of the cycle of a small turbojet engine involves components inlet and outlets temperatures, pressures, mass flows and thermo-mechanical features of the engine such as overall efficiency, specific fuel consumption and thrust. The description of thermodynamic equations can be found in any number of texts [13-15].

2.2. Thermodynamic Relations

The adiabatic efficiency is the ratio of work required or acquired for a reversible change in the pressure to the actual work needed for the real process for the same change in the pressure. The compressor and turbine efficiencies are given by [17]

$$\eta_c = \frac{h_{t3s} - h_{t1}}{h_{t3} - h_{t1}} \tag{1}$$

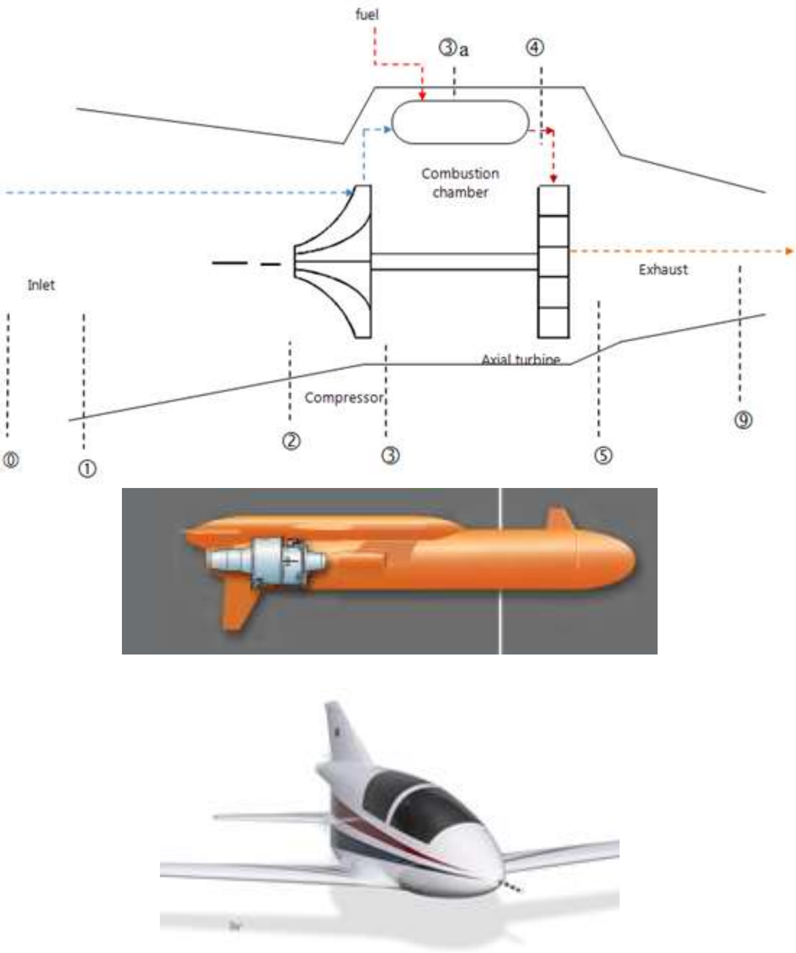


Figure 1. UAV's turbojet engine and location in a target drone and microjet aircraft [16].

$$\eta_t = \frac{h_{t4} - h_{t5}}{h_{t4} - h_{t5s}} \tag{2}$$

The polytrophic efficiency, showing the effect of a technology in a way that is independent of pressure ratio described as the efficiency for an infinitesimally small compression and expansion.

$$\eta_{poly} = \frac{\gamma - 1}{\gamma} \frac{dp_t}{p_t} \frac{T_t}{dT_t} \tag{3}$$

The polytrophic efficiency can be expressed as a measure of entropy generation using Gibbs equation [17].

$$\eta_{poly} = \left(1 - \frac{T_t ds}{dh_t}\right)^{\pm 1} \tag{4}$$

where the exponent is + for the compression and -1 for the expansion.

Gas flows through the small turbojet engine are taken to be mixtures of perfect gases with variable $C_p\,(T)$. The flow is assumed to be made of a number of discrete elements, each with its own gas constant, enthalpy of formation, and temperature- dependent variable specific heat. The specific heat is a function of temperature. The enthalpy of formation h_F (defined at standard temperature T_{std}) and gas constant R is constant each constituent. The enthalpy $h(T)$ and entropy complement can be calculated [17].

$$h(T) = h_F + \int_{T_{std}}^{T} C_p(T)\,dT \tag{5}$$

$$s'(T) = \int_{T_{std}}^{T} \frac{C_p(T)\,dT}{T} \tag{6}$$

The composition of the mixture is characterized by the mass fraction vector $\vec{\alpha}$, where α_i represents the mass fraction of the i^{th} constituent. The mixture properties can be calculated as

$$R = \sum_i \alpha_i R_i = \vec{\alpha}.\vec{R} \tag{7}$$

$$C_p(T) = \sum_i \alpha_i C_{pi}(T) = \vec{\alpha}.\vec{C}_p(T) \tag{8}$$

$$h(T) = \sum_i \alpha_i h_i(T) = \vec{\alpha}.\vec{h}(T) \tag{9}$$

$$s'(T) = \sum_i \alpha_i s_i'(T) = \vec{\alpha}.s'(T) \tag{10}$$

Combining Gibbs equation, perfect gas definition and from definition of *h(T)*, the temperature and pressure changes can be related for an adiabatic work given an initial state *(i)* [17].

$$p(T) = p(T_i)\exp\left(\eta_{poly}^{\pm 1}\frac{s'(T) - s'(T_i)}{R}\right) \tag{11}$$

Environmental condition are characterized by a specified gas mixture $\vec{\alpha}_0$, static temperature T_0, and static pressure P_0.The stagnation properties can be calculated from a specified Mach number M_0.

$$C_{p0} = C_p(T_0) \tag{12a}$$

$$h_0 = h(T_0) \tag{12b}$$

$$V_0 = M_0\sqrt{\frac{C_{p0}R_0T_0}{C_{p0} - R_0}} \tag{12c}$$

$$h(T_0) - h_0 - 1/2V_0^2 = 0 \rightarrow T_{t0} \tag{12d}$$

$$p_{t0} = p_0 \exp\left(\eta_{poly}^{\pm 1}\frac{s'(T_{t0}) - s'(T_0)}{R}\right) \tag{12e}$$

$$h_{t0} = h(T_{t0}) \tag{12f}$$

Any losses incurred in diffuser can be defined as inlet pressure ratio π_d.

$$T_{t1} = T_{t0} \tag{13a}$$

$$P_{t1} = \pi_d P_{t0} \tag{13b}$$

$$h_{t1} = h_{t0} \tag{13c}$$

The compressor calculation is given as follows:

$$\left(\frac{s'(T_{t3}) - s'(T_{t1})}{R}\right) - \ln\left(\frac{\pi_c}{\eta}\right) = 0 \rightarrow T_{t3} \tag{13d}$$

$$P_{t3} = \pi_c P_{t1} \tag{13e}$$

$$h_{t3} = h(T_{t3}) \tag{13f}$$

The combustion process is characterized by its initial and final temperatures, T_{t3} and T_{t4} and the fuel type, characterized by its composition $\vec{\beta}$, its temperature T_f, and vector representing the mass fraction change in air due to combustion $\vec{\gamma}$. Conservation of energy gives the required fuel-to air ratio *f*, leading to final mass fraction vector $\vec{\alpha}_4$.

$$f = \frac{\vec{\alpha}_0 \left(\vec{h}\left(T_{t4}\right) - \vec{h}\left(T_{t3}\right) \right)}{\vec{\beta}.\vec{h}\left(T_f\right) - \vec{\gamma}\vec{h}\left(T_{t4}\right)} \tag{14a}$$

$$\vec{\alpha}_4 = \frac{\vec{\alpha}_0 + f\vec{\gamma}}{1+f} \tag{14b}$$

Any losses in the combustor is characterized by a total pressure ratio of burner π_b .

$$P_{t4} = \pi_b P_{t3} \tag{14c}$$

The enthalpy drop in the turbine is calculated from the enthalpy rises across the compressor, and the pressure drop is calculated from the turbine isentropic efficiency.

$$\Delta h = \frac{\left(h_{t3} - h_{t1}\right)}{1+f} \tag{15a}$$

$$h_{t5} = h_{t4} - \Delta h \tag{15b}$$

$$h_{t5} - h(T_{t5}) = 0 \rightarrow T_{t5} \tag{15c}$$

$$p_{t5} = p_{t4}\exp\left(\frac{s'\left(T_{t5}\right) - s'\left(T_{t4}\right)}{\eta R} \right) \tag{15d}$$

A convergent exhaust nozzle of the small turbojet engine accelerates the flow exiting from the turbine to provide propulsive force. Any loss incurred in the exhaust is characterized by total pressure ratio π_n .the nozzle exit pressure is assumed to be equal to the ambient pressure P_0.

$$T_{t9} = T_{t5} \tag{16a}$$

$$P_{t9} = \pi_n P_{t5} \tag{16b}$$

$$h_{t9} = h_{t5} \tag{16c}$$

$$P_9 = P_0 \tag{16d}$$

$$\left(\frac{s'\left(T_{t9}\right) - s'\left(T_9\right)}{R} \right) - \ln\left(\frac{P_{t9}}{P_9} \right) = 0 \rightarrow T_8 \tag{16e}$$

$$V_9 = \sqrt{2\left[h_{t9} - h\left(T_9\right)\right]} \tag{16f}$$

$$M_9 = V_9 \sqrt{\frac{C_p\left(T_9\right) R T_9}{C_p\left(T_9\right) - R}} \tag{16g}$$

If M_9 is greater than unity, the choked condition is accepted, and the velocity and static pressure are calculated again, as is the density, which is needed in the calculation of a specific thrust for a choked nozzle.

$$M_9 = 1 \tag{17a}$$

$$h_{t9} - h(T_{t9}) - \frac{M_9^2 C_p\left(T_{t9}\right) R T_{t9}}{2\left(C_p\left(T_{t9}\right) - R\right)} = 0 \rightarrow T_9 \tag{17b}$$

$$V_9 = \sqrt{2\left[h_{t9} - h\left(T_9\right)\right]} \tag{17c}$$

$$p_9 = p_{t9}\exp\left(\frac{s'\left(T_9\right) - s'\left(T_{t9}\right)}{R} \right) \tag{17d}$$

$$\rho_9 = \frac{P_9}{RT_9} \tag{17e}$$

The propulsive efficiency of the turbojet engine η_{prop} is defined as the rate of mechanical energy added to the working fluid to the thrust power produced and given by

$$\eta_{prop} = \frac{FV_0}{\dot{m}_0 \Delta KE} \tag{18}$$

The thermal efficiency of the engine is the rate that kinetic energy is added to flow divided by the rate of fuel energy use

$$\eta_{th} = \frac{\dot{m}_0 \Delta KE}{\dot{m}_f h_{PR}} \tag{19}$$

The overall efficiency is expressed as the product of the thermal efficiency and propulsive efficiency.

$$\eta_{overall} = \eta_{th}.\eta_{prop} = \frac{FV_0}{\dot{m}_f h_{PR}} \tag{20}$$

Turbojet engines are evaluated by the specific fuel consumption (*SFC*),

$$SFC = \frac{\dot{m}_f}{F} \tag{21}$$

SFC can also be expressed as follows:

$$SFC = \frac{V_0}{\eta_0 h_{PR}} \tag{22}$$

2.3. Thrust Force

For the turbojet engine, thrust force is another performance metric considered. Thrust force of an aero-engine can be derived from basic conservation laws of mass and momentum in their integral forms the momentum and continuity equations. Consider a schematic diagram for an engine with a of pod installation (Figure 2).

Control volume passes through the engine exhaust at (2) and extends far upstream at (1). In Figure 2, the two sides of the control volume are parallel to the flight velocity *u*. The surface area at stations (1) and (2) are equal and denoted by *A*. The exhaust area for gases leaving the engine has an area A_e at (2), while stream tube of air entering the engine is A_i at (1). The velocity and pressure over station (1) are *u* (which is also flight velocity) and P_a (ambient pressure at same altitude), respectively.

Over the station (2), velocity and pressure are same at station (1) except over the exhaust area A_e where the values are to be u_e and P_e. The flow is steady within the control volume and external flow is reversible [18]. The continuity equation gives Eq.23 (a) for the control volume [18],

$$\frac{\partial}{\partial t}\iiint_{CV} \rho dv + \iint_{CS} \rho \bar{u} d\bar{A} = 0 \tag{23a}$$

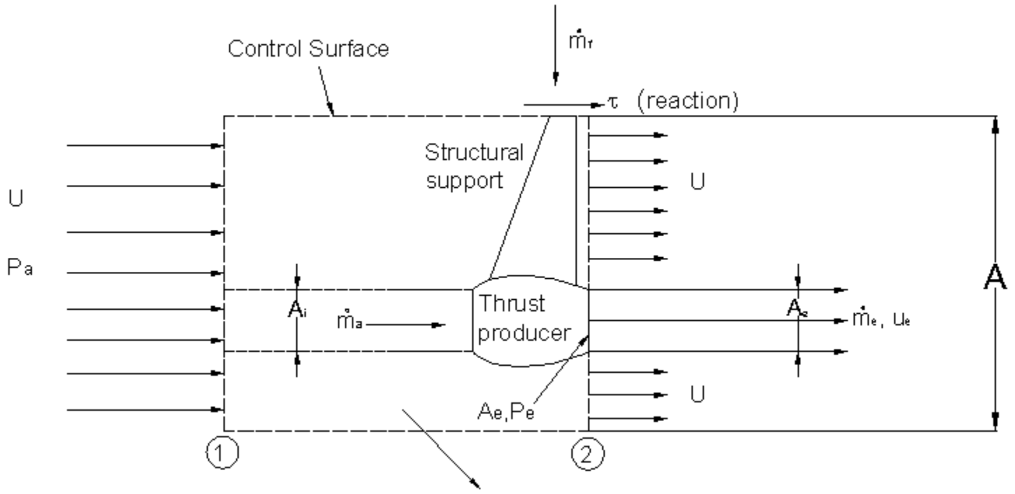


Figure 2. A schematic diagram for a turbojet engine

According to the momentum equation,

$$\sum \bar{F} = \frac{\partial}{\partial t}\iiint_{CV} \rho \bar{u} dv + \oiint_{CS} \bar{u}\left(\rho \bar{u} d\bar{A}\right) = 0 \tag{23b}$$

From Eq.23 (a) and Eq.23 (b), net thrust force τ can be yielded for an aero engine as follows [73]:

$$\tau = \dot{m}_a\left[(1+f)u_e - u\right] + (P_e - P_a)A_e \tag{24}$$

On a rate basis, the integral form of the conservation of energy may be written as [74]

$$\dot{Q} - \dot{W}_s - \dot{W}_{shear} - \dot{W}_{other} = \frac{\partial}{\partial t}\int_{CV} e\rho dv + \int_{CS}\left(e + pv\right)\rho u.dA \tag{25}$$

Where $\dot{Q}$ is heat transfer rate, $\dot{W}_s$ is work transfer rate at surface, $\dot{W}_{shear}$ is the work rate due shear, $\dot{W}_{other}$ is work from all other forms (electrical, shaft etc.), $\frac{\partial}{\partial t}\int_{CV} e\rho dv$ is time rate of change of energy inside control volume, $\int_{CS}\left(e+pv\right)\rho u.dA$ is flux of energy across control surface, *e* is specific energy

2.4 Second Law of Thermodynamics and Exergy

The Gibbs function gives a relation between entropy and internal energy. In time averaged form, it can be given as follows *[20]:*

$$T\nabla s = \nabla e + p\nabla \frac{1}{\rho} \tag{26}$$

Inserting the steady-state expression of the internal energy [20]:

$$\nabla.\left(\rho \delta e \mathbf{V}\right) = -p\nabla.\mathbf{V} + \left(\overset{=}{\tau}\nabla\right).\mathbf{V} - \nabla \mathbf{q} \tag{27}$$

First Law or 'energy' analysis takes no account of the energy source in terms of its thermodynamic quality. It enables energy or heat losses to be estimated, but yields only limited information about the optimal conversion of energy. In contrast, the Second Law of Thermodynamics indicates that, whereas work input into a system can be fully converted to heat and internal energy, not all the heat input can be converted into useful work [21]. The exergy loss in a system or component is determined by multiplying the absolute temperature of the surroundings by the entropy increase. Exergy methods also help in understanding and improving efficiency, environmental and economic performance as well as sustainability [21].

Note that, whereas energy is a conserved quantity, exergy is not and is always destroyed when entropy is produced. In the absence of electricity, magnetism, surface tension and nuclear reaction, the total exergy of a system $\dot{E}x$ can be divided into four components, namely (i) physical exergy $\dot{E}x^{PH}$ (ii) kinetic exergy $\dot{E}x^{KN}$ (iii) potential exergy $\dot{E}x^{PT}$ and (iv) chemical exergy $\dot{E}x^{CH}$ [21].

In the perspective of producing work, we can write that [20]

$$Energy = Exergy + Anergy \;\Leftrightarrow Total = Useful + Useless \tag{28}$$

For an open system, Eq.(16) can be written mathematically as [20]

$$ex = (h_t - h_{t0}) - T_0(s - s_0) = \delta h_t - T_0 \delta s \tag{29}$$

Time-averaged change in exergy can be written as [20]:

$$\nabla.(\rho ex\mathbf{V}) = \nabla.(\rho \delta h_t \mathbf{V}) - T_0 \nabla.(\rho \delta s \mathbf{V}) \tag{30}$$

If we neglect the heat transfer across the outer boundary as well as viscous,

$$-\int_{S_A} \rho ex(\mathbf{V.n})dS = -\int_{v} \nabla.\rho ex\mathbf{V}dv + \int_{S_O} \rho ex(\mathbf{V.n})dS + \int_{S_W} \rho ex(\mathbf{V.n})dS \tag{31}$$

From above equations, following exergy balance can be written [20]:

$$\dot{E}x_{eng} + \dot{E}x_q = W\dot{\Gamma} + \dot{E}x_m + \dot{E}x_{th} + \dot{A}_{tot} \tag{32a}$$

Left-hand-side terms represent exergy sources supplies, whereas right-hand-side terms represent exergy outflows and sinks, except for $W\dot{\Gamma}$, which is a reversible accumulation/restitution of exergy. The rate of exergy outflow is decomposed into $W\dot{\Gamma} + \dot{E}x_m + \dot{E}x_{th}$, and the total anergy generated within control volume ($\dot{A}_{tot}$)[20],

$$\dot{A}_{tot} = \dot{A}_{\Phi} + \dot{A}_{\nabla T} + \dot{A}_w \tag{32b}$$

The aircraft surface has been split in two surfaces: one solid body surface S_B ,which may be non-adiabatic, and one permeable engine or propulsion surface S_{eng} , on which $\mathbf{V.n} \neq 0$. Note that $S_A = S_B \cup S_{eng}$ [20].

The rate of exergy supplied by an engine is:

$$\dot{E}x_{eng} = \int_{S_{eng}} -\rho \delta h_t (\mathbf{V.n})dS - T_0 \int_{S_{eng}} -\rho \delta s (\mathbf{V.n})dS \tag{33}$$

The first term is the total power supplied to the flow, whereas the second term represents all unavoidable thermodynamic inefficiencies ad aerodynamic losses within the engine. The combination of both forms the exergy delivered by the engine to the fluid [20]. Thermodynamic analysis uses the energy and exergy parameters at the entrance and exit of the system components. For that reason, the values at those locations will be calculated by using the flow parameters.

The chemical exergy is determined as [22]:

$$\overline{ex_{ch,i}} = \sum x_i \overline{ex_i}^{ch} + \bar{R}T_0 \sum x_i \ln x_i \tag{34}$$

The specific chemical exergy of liquid fuel on a unit mass basis can be determined as follows [23]:

$$\frac{ex_{ch,f}}{h_{PR}} = \gamma_f \cong 1.0401 + 0.01728\frac{H}{C} + 0.0432\frac{O}{C} + 0.2196\frac{S}{C}\left(1 - 2.0628\frac{H}{C}\right) \tag{35}$$

where γ_f denotes the fuel exergy grade function which is calculated to be 1.067893 for the kerosene of type JP8. H, C, O and S are the mass fraction of hydrogen, carbon, oxygen and sulphur, respectively. For the kerosene fuel given in chemical formula as $C_{12}H_{23}$, sulphur is neglected in calculation due to nearly zero fraction of it in fuel composition. The general combustion equation and combustion constant is given in Eq. (36) [23]:

$$C_{12}H_{23} + \lambda_1 \begin{pmatrix} 0.7748\ N_2 \\ +0.2059\ O_2 \\ +0.0003\ CO_2 \\ +0.019\ H_2O \end{pmatrix} \rightarrow \begin{pmatrix} \lambda_2 CO_2 \\ +\lambda_3 H_2O \\ +\lambda_4 O_2 \\ +\lambda_5 N_2 \end{pmatrix} \tag{36}$$

Numerous ways of formulating exergy efficiency for various energy systems are given in detail elsewhere. It is very useful to define efficiencies based on exergy (sometimes called Second Law efficiency). There is no standard set of definitions in the literature. General overall energy efficiency (η_o) and exergy efficiency (η_{ex}) can be defined as follows

$$\eta_o = 1 - \frac{\text{Energy loss}}{\text{Energy inputs}} \; , \; \eta_{ex} = 1 - \frac{\text{Exergy loss+Exergy destruction}}{\text{Exergy inputs}} \tag{37}$$

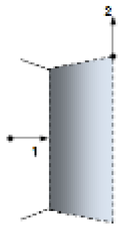
Here, exergy efficiency is defined as the ratio of total exergy output to total exergy input, i.e.

$$\eta_{ex} = \frac{\dot{E}x_i}{\dot{E}x_o} = 1 - \frac{\dot{E}x_{dest} + \dot{E}x_{loss}}{\dot{E}x_i} \tag{38}$$

where ‘‘out’’ stands for ‘‘net output’’ or ‘‘product’’ or ‘‘desired value’’ or ‘‘benefit’’, and ‘‘in’’ stands for ‘‘given’’ or ‘‘fuel’’. It is obvious that reducing losses and destructions will increase the efficiencies. As the exergy efficiency approaches minimum, the environmental impact approaches maximum, while sustainability approaches minimum [24].

The relations given in this section are applied to the engine along with its components given below and following, which includes energy and exergy definitions, is obtained for the small turbojet components given as follows:

<ins>For Inlet (I):</ins>

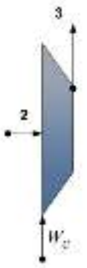


1-2 Adiabatic diffuser: $h_{t2} = h_{t1} + (1/2)V_0^2$ (39a)

Exergy rate of product: $\dot{E}x_2$ (39b)

Exergy rate of fuel: $\dot{E}x_1$ (39c)

<ins>For centrifugal compressor (C):</ins>

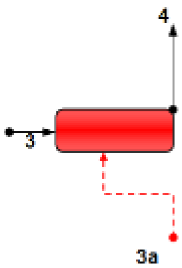


2-3 Adiabatic compressor : $\dot{W}_C = h_{t1} - h_{t2}$ (40a)

Exergy rate of product: $\dot{E}x_3 - \dot{E}x_2$ (40b)

Exergy rate of fuel: $\dot{W}_C$ (40c)

<ins>For reverse-flow combustion chamber (CC):</ins>

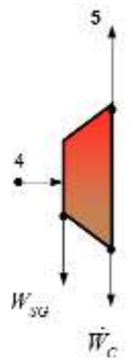


3-4 Combustion process: $\dot{Q}_{in} = h_{t4} - h_{t3}$ (41a)

Exergy rate of product: $\dot{E}x_4$ (41b)

Exergy rate of fuel: $\dot{E}x_{3a} + \dot{E}x_3$ (41c)

<ins>For axial-flow turbine (T):</ins>



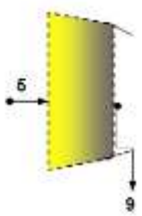
4-5 Adiabatic turbine to drive compressor and starter generator:

$$\dot{W}_T = h_{t4} - h_{t5} = -\dot{W}_C - \dot{W}_{SG} \tag{42a}$$

Exergy rate of product: $\dot{W}_C + \dot{W}_{SG}$ (42b)

Exergy rate of fuel: $\dot{E}x_4 - \dot{E}x_5$ (42c)

For exhaust nozzle (N):



5-9 Adiabatic nozzle: $\dot{V}_9 = \sqrt{2\left(h_{t5} - h_{t9}\right)}$ (43a)

Exergy rate of product: $\dot{E}x_9$ (43b)

Exergy rate of fuel: $\dot{E}x_5$ (43c)

Exergetic improvement potential (IP) rate is given by [11]

$$I\dot{P}_i = \left(1 - \eta_{ex,i}\right)\left(\dot{E}x_{fuel,i} - \dot{E}x_{pro,i}\right) \tag{44}$$

Fuel depletion ratio is given by [11]

$$\chi_i = \frac{\dot{E}x_{des,i}}{\dot{E}x_{des,tot}} \tag{45}$$

Exergy destruction rate measures the rate of exergy destruction or consumption due to irreversibilities within the device, and is equivalent for steady-state processes to the difference between the exergy inputs and outputs. It is expressible as [11]

$$\dot{E}x_{des,i} = \dot{E}x_{fuel,i} - \dot{E}x_{pro,i} \tag{46}$$

Relative irreversibility is defined as follows [11]:

$$\delta_i = \frac{\dot{E}x_{des,i}}{\dot{E}x_{fuel,tot}} \tag{47}$$

Productivity lack, which is similar to the fuel depletion ratio, gives the product loss in the form of exergy destruction or shows how much product exergy potential is lost due to exergy destructions. Productivity lack ξ is expressible as [11]

$$\xi_i = \frac{\dot{E}x_{des,i}}{\dot{E}x_{pro,tot}} \tag{48}$$

Fuel and product exergy factors measure the parts of the fuel and product exergy values for a component as a fraction of the total fuel and product exergy values for the engine, respectively. The fuel exergy factor can be written as [11]

$$f_i = \frac{\dot{E}x_{fuel,i}}{\dot{E}x_{fuel,tot}} \tag{49}$$

and the product exergy factor [11]

$$p_i = \frac{\dot{E}x_{pro,i}}{\dot{E}x_{pro,tot}} \tag{50}$$

In this study, to calculate thermodynamic parameters using equations based on tdata, a MATLAB code has been developed by the author.

4. RESULTS AND DISCUSSION

The performance outputs of four main components (compressor, combustion chamber, turbine and exhaust) and the overall engine are quantified and illustrated as performance plots using parameters given in Table 1 for comparison purposes.

In this study, the reference altitude was taken to be 8,000 m and the atmospheric pressure and temperature are 30.73 kPa and 229.5 K, respectively.

Table 1. Turbojet engine design and performance parameters.

Parameter	*Value*
Flight altitude (m)	8,000
Ambient temperature (K)	229.5
Ambient pressure (kPa)	30.73
Compressor isentropic efficiency	0.78
Burner efficiency	0.85
Turbine isentropic efficiency	0.78
Nozzle’s total pressure ratio	0.90
Inlet maximum pressure ratio	0.90
Shaft mechanic efficiency	0.89
Static pressure ratio at the exhaust	0.90
Air mass flow (kg/s)	1.634
Fuel heating value (kJ/kg)	42,800
Burner pressure loss	0.85
Diffusor pressure loss	0.95

All components are irreversible but they are adiabatic (except combustion chamber). The entropy of the air in the compressor increases due to friction, turbulence, separate through the compressor. In addition to this, the outlet temperature of the compressor is higher than the isentropic temperature. Increase in temperature depends on the compressor efficiency. Thus isentropic efficiencies for the compressor and turbine are taken to be 0.78. Friction at the air intake reduces the total pressure from its ambient value and increases entropy. The total temperature at the inlet of the compressor is higher than in the isentropic case, which depends on the intake efficiency. So, the inlet maximum pressure ratio of the air intake is taken to be 0.90 in the exergy analysis. Losses in the combustion chamber are encountered owing to physical characteristics of the fuel, imperfect combustion and thermal losses. These losses are handled by introducing the burner efficiency. The burner pressure loss and burner efficiency are take to be 0.85 and 0.90, respectively. The stagnation pressure at the outlet of the combustion chamber is less than its value at inlet. The pressure drop is either given as a percentage or a definite value. The burner loss ratio is taken to be 0.80 because of the fluid friction. In the axial-flow turbine, an increase in the entropy is encountered due to friction. In addition to this, outlet temperature of the turbine is higher than that of isentropic case. This process is associated with the turbine efficiency. Turbine isentropic efficiency of the small turbojet engine is taken to be 0.78 in the analysis. The expansion process in the exhaust is influenced by the skin friction. The exhaust static and total pressure ratio value are taken to be 0.90.

To analysis exergetic performance of turbojet engine, computer program was developed in MATLAB environment. From Figures 3 to Figure 5, energy and exergy analysis results are summarized.

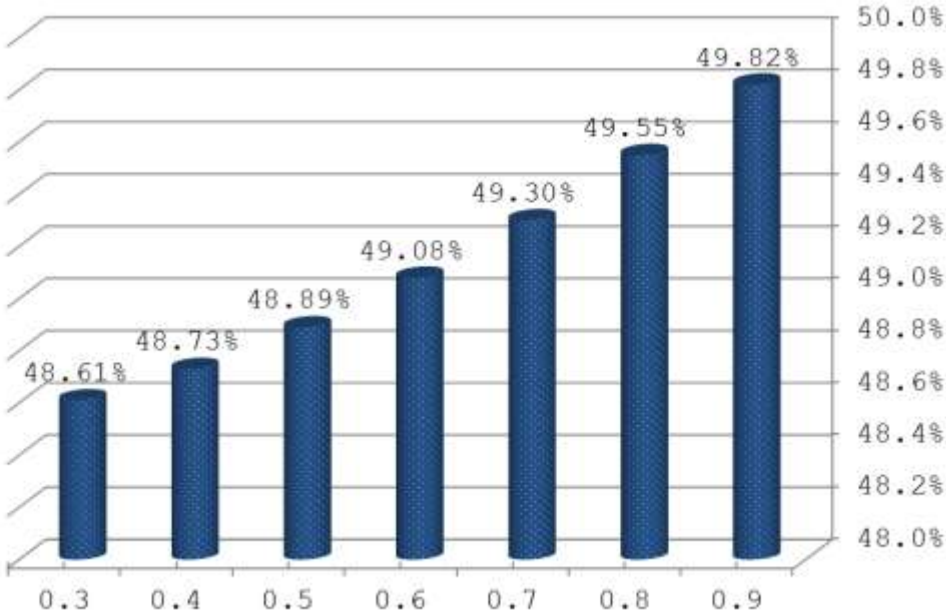


Figure 3. Effect of aircraft Mach number on the engine exergy efficiency at 8,000 m altitude

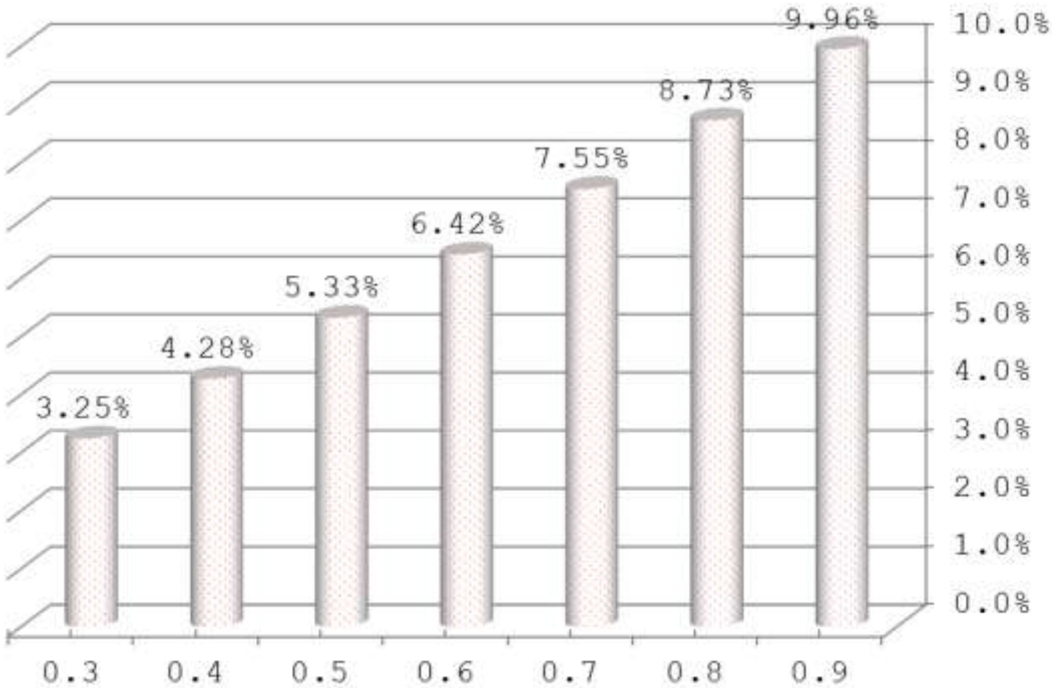


Figure 4. Effect of aircraft Mach number on the engine overall efficiency at 8,000 m altitude

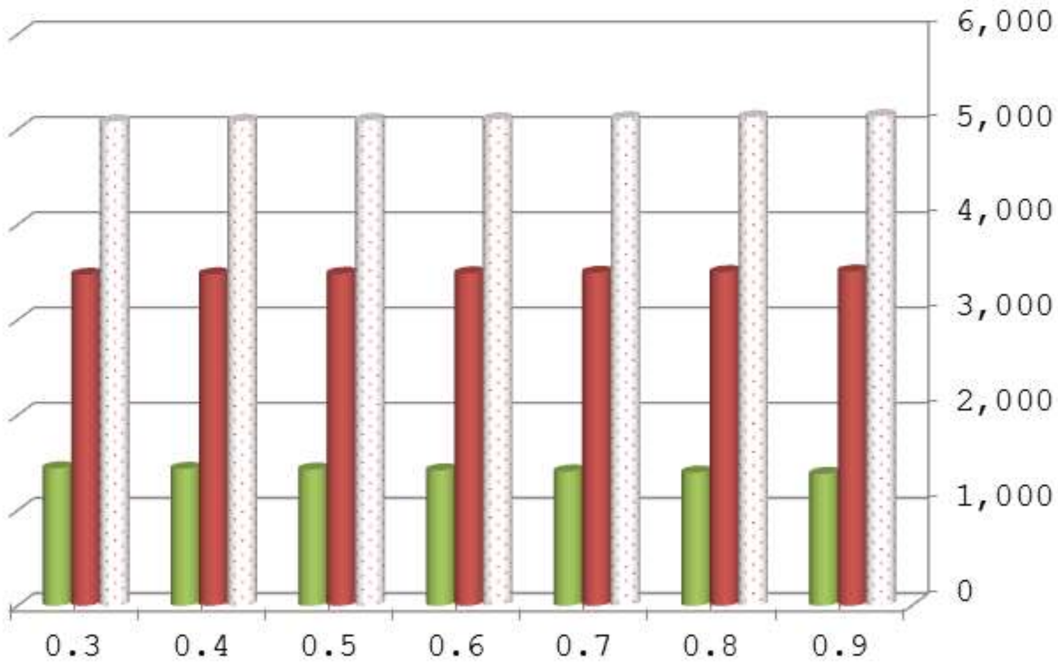


Figure 5. Effect of aircraft Mach number on the engine total fuel, product exergy and exergy destruction

4. CONCLUSION

Gas-turbine engines are candidate propulsion systems for Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance (C4ISR) UAV (unmanned aircraft), UAVs—these aircraft are characterized by medium or long range and/or endurance, medium to high altitude, medium to high subsonic speeds, and sensor and communication payloads. Gas-turbine engines are candidate propulsion systems for C4ISR UAVs, combat UAVs, and virtually all rotorcraft UAVs. Power requirements may range from 445 N (100 pounds of thrust) to perhaps 67 kN (15,000 pounds of thrust).
In this study, we have presented flight Mach number effect on the exergetic and exergetic performance of a small turbojet engine with kerosene-fired an altitude of 8,000 m. In this regard, general energy and exergy relations were applied to each of the engine components, while exergy and energy efficiency relations were derived for the engine components and the whole engine.

a) The results of the exergy and energy analysis performed here on a small turbojet engine used in auxiliary power unit, one-manned and unmanned aircraft indicate that aircraft flight Mach number are responsible for a majority of the first law efficiency.
b) The overall engine efficiency of the small turbojet engine is shown to decrease by approximately from 3.25% to 9.96% for 0.3 to 0.9 flight Mach number.
c) The exergy efficiency remains nearly constant, exhibiting only a slight decrease with flight Mach number (less than 2.5%).
d) Engine exergy destruction is also slight decrease with flight Mach number (approximately 4.1%).
e) Exergy efficiency values were found to be 89.45% for the centrifugal compressor, 61.11 % for the combustion chamber and 89.21% for the turbine, and 84.15% for the exhaust.
f) Engine performance parameters such as specific fuel consumption and thrust is 64.97 g (kN. s)$^{-1}$ and 963.49 N, respectively.

Nomenclature

$\dot{A}_q$	Rate of heat anergy supplied by conduction, $J{\cdot}s^{-1}$
$\dot{A}_{tot}$	Rate of total anergy generation, $J{\cdot}s^{-1}$

$\dot{A}_w$	Rate of anergy generation by shock waves, $J \cdot s^{-1}$
$\dot{A}_{\nabla T}$	Rate of anergy generation by thermal mixing, $J \cdot s^{-1}$
$\dot{A}_{\phi}$	Rate of anergy generation by viscous dissipation, $J \cdot s^{-1}$
C_p	specific heat ratio , kJ/kg
d_m	m_{th} component of the expected output vector
ex	specific exergy, kJ/kg
$\overline{ex}$	specific exergy, kJ/kmol
f	fuel exergy factor; fuel-air ratio
F	Thrust (Newton)
h	specific enthalpy , kJ/kg
h_{PR}	fuel heating value, kJ/kg
I	Inlet
i	component
JP8	Jet fuel for the turbojet engine
KE	kinetic energy, kJ/kg
$\dot{m}$	mass flow rate, kg/s
M	Mach number
p	product exergy factor
pe	potential energy, kJ/kg
P_s	Specific power, kW kg^{-1}
q	Heat flux by conduction, J s^{-1}
Q	Heat, kJ
Φ	Dissipation rate per unit volume, J $s^{-1}m^{-3}$
R	ideal gas constant
ρ	Density, kg m^3
s	Specific entropy, kJ kg^{-1} K^{-1}
S	Entropy, kJ K^{-1}
SFC	specific fuel consumption, g/(kN.s)
T	temperature, K
τ	Thrust, N
$\bar{\bar{\tau}}$	Viscous stress tensor, N
x_i	x th element for combustion process
UAV	unmanned air vehicle
V	Velocity, $m.s^{-1}$
V	$(V_0$+ u)**x**, v**y**, w**z**, fluid velocity vector, ms^{-1}
$\dot{W}$	work, kJ/s
Δw	Incremental change in weight
Γ	Weight specific aircraft energy height, m
x	fraction of each combustion equation species
y	exergy destruction ratio

Greek Letters

α	mass fraction
β	composition
γ	ratio of specific heats
η	efficiency
π	pressure ratio
ρ	density
χ	fuel depletion ratio
δ	relative irreversibility; dimensionless pressure
ξ	productivity lack
$\Psi_{1,...,n}$	combustion element coefficient

θ	dimensionless temperature

Subscripts and superscripts

b	burner
C	compressor
ch	chemical
corr	corrected
d	diffuser
dest	destruction
f	fuel; fuel-air ratio
fuel	fuel exergy
F	formation
i	ith component
in	input
kn	kinetic
loss	exergy loss
N	nozzle
out	output
poly	polytrophic
ph	physical
pro	product
prop	propulsive
pt	potential
r	system boundary
ref	reference value (i.e. sea level)
s	isentropic
SG	starter generator
std	standard
t	stagnation
T	Turbine
th	thermal
tot	total
0..9	station numbering of the engine
$\rightarrow$	vector statement

REFERENCES

[1] DİNÇ, A., "Optimization of a Turboprop UAV for Maximum Loiter and Specific Power Using Genetic Algorithm", International Journal of Turbo&Jet Engine, DOI 10.1515/tjj-2015-0030, 2015.

[2] FAA,Federal Aviation Administration, Aviation Safety Unmanned Aircraft Program Office (UAPO), Interim Operational Approval Guidance. Unmanned Aircraft Systems Operations in the U. S. National Airspace System. 2008.

[3] U.S. Department of Defense. Office of the Secretary of Defense 2007–2032 Unmanned Systems Roadmap, 2007.

[4] ANDREU, L. Performance of a ducted micro-turbojet engine. Master's thesis, Naval Postgraduate School, Monterey, CA, USA, 1999.

[5] GUHA, A., "Optimization of aero gas turbine engines", The Aeronautical Journal; pp.345-358, 2001.

[6] GUHA, A., "Performance and optimization of gas turbine engine with real gas effects", Proceedings Institution of Mechanical Engineers, 215, 507-512, 2001.

[7] TURAN, O, AYDIN, H., "Exergetic and exergo-economic analyses of an aero-derivative gas turbine engine", Energy, Vol.74, 638-650, 2014.

[8] ATILGAN, R., TURAN, O., ALTUNTAS, O., AYDIN, H., SYNYLO, K., "Environmental impact assessment of a turboprop engine with the aid of exergy", Energy; 58, 664-671, 2013.

[9] BAKLACIOGLU, T., TURAN, O., AYDIN, H., "Dynamic modeling of exergy efficiency of turboprop engine components using hybrid genetic algorithm-artificial neural networks", Energy, 86:709-721, 2015.

[10] TURAN, O.," Effect of reference altitudes for a turbofan engine with the aid of specific-exergy based method", International Journal of Exergy, 11, 252-270, 2012.
[11] TURAN, O.," An exergy way to quantify sustainability metrics for a high bypass turbofan engine", Energy, 86,722-736, 2015.
[12] TURAN, O., "Exergetic effects of some design parameters on the small turbojet engine for unmanned air vehicle applications", Energy, 46, 51-61,2012.
[13] CUMPTSY, NA., Jet propulsion: A simple guide to the aerodynamic and thermodynamic design and performance of jet engines. Cambridge University Press, Second Edition, 2003.
[14] KERREBROCK, J.L.. Aircraft engines and gas turbines. MIT Press, Second Edition, 1992.
[15] SARAVANAMUTTO, H.I.H., ROGERS, G..FC., COHEN, H., Gas turbine theory. Prentice Hall, 5th Edition, 2001.
[16] Microturbo http://www.safran-power-units.com/ (access date: May, 12,2016)
[17] HALL, D.K., Performance limits of axial turbomachine stages. Master of Science Thesis. MIT, USA, 2011.
[18] EL-SAYED, A. F., Aircraft propulsion and gas turbine engines, CRC Press, 2008.
[19] JOHN, H.D., CAMBEROS, J.A., MOORHOUSE, D.J., "Benefits of exergy-based analysis for aerospace engineering applications part I", International Journal of Aerospace Engineering, 1-11, 2009.
[20] ARNTZ, A., ATİNAULT, O., "Exergy-based formulation for aircraft aeropropulsive performance assessment: theoretical development", AIAA Journal, 53 (6); 1627-39, 2015.
[21] HEPBAŞLI, A. A., "Key review on exergetic analysis and assessment of renewable energy resources for a sustainable future", Renewable and Sustainable Energy Reviews,; 12, 593-661, 2008.
[22] BEJAN, A., TSATSARONIS, G., MORAN, M., Thermal design and optimization. USA,Wiley; 1996.
[23] KOTAS, T.J., The exergy method of thermal power plants. Malabar, FL, Krieger Publishing Company; 1995.
[24] DİNCER, I. Environmental and sustainability aspects of hydrogen and fuel cell systems. International Journal of Energy Resources, 31, 29–55, 2007.