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Research Article

Optimization of energy and exergy parameters for a conceptual afterburning turbojet engine

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ABSTRACT

In this study, parametric cycle analysis of a conceptual turbojet engine with an afterburner (TJEAB) was conducted at sea level conditions-zero Mach. Based on this analysis, exergetic sustainability parameters of TJEAB were scrutinized for military mode (MM) and afterburner mode (ABM). Constitutively, several design parameters of TJEAB were chosen so as to optimize performance and exergetic parameters which consist of specific fuel consumption (SFC), overall efficiency, exergy efficiency, environmental effect factor (EEF) and exergetic sustainability index (ESI). In this context, compressor pressure ratio (CPR), turbine inlet temperature (TIT) were preferred due to high effect of these variables on engine performance. CPR ranges from 4 to 11 whereas TIT varies from 1150 K to 1550 K. According to optimization of performance parameters, minimum SFC was achieved as 28.59 g/kN.s at MM and 43.95 g/kN.s at ABM. On the other hand, maximum overall efficiency is determined as to be 13.07 % at MM and to be 8.5 % at ABM. As for exergetic parameters, exergy efficiency was calculated as maximum with 30.85 % at MM and 23.2 % at ABM. Finally, maximum exergetic sustainability index of TJEAB was computed as 0.446 at MM and 0.269 at ABM. It is thought that energetic and exergetic parameters analyzed in this analysis could guide in designing turbojet engines in terms of lower fuel consumption thereby environmental-benign.

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INTRODUCTION

Many countries have revised their energy policies so as to increase awareness about consumption of the world's energy resources. Therefore, several strict measures have been taken for wasted management [1]. Also, scientific humans have focused on improving efficiency of thermal systems by developing new tools to better use the limited source [2]. There are two options so as to prevent the rapid depletion of energy sources. The first one is the improvement of efficiency of thermal systems whereas the second one is investigation of new energy sources instead of using

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for fossil fuels. Recently, hybrid systems, fuel-cell technologies and biofuels have sparked interest to the engineers [3-6]. In this context, optimization of energetic and exergetic parameters for propulsion system is being deployed as the main technique in the effort to evaluating the gas turbine engine performance. It is well known that the overall efficiency of propulsion system could be determined by employing the first law of thermodynamics which only provides insight about quantity of energy analysis. As for the second law of thermodynamics, it could be addressed to quality of energy for system improvement [7]. The existing energy degradation, entropy production and exergy destruction in each component of propulsion system could be estimated by exergy analysis which incorporates the both laws of thermodynamics [2]. Considering analysis of propulsion system, exergy analysis has played a key role due to its usefulness in computing and estimating the true amount of irreversibility occurred in each component [8]. In other words, the main aim for using of exergetic tool is to understand the sources of inefficiency and to reveal the quality of energy sources consumed. The first and second law efficiency of propulsion systems have been analyzed by coupling thermodynamics and optimization methods throughout the last decades.

Turbojet engines are candidate propulsion systems to be employed at several military and civil aircraft applications such as unmanned aircraft [9]. These are considered as alternative for aircraft technologies that depend on fossil-fuel. In this context, micro and small turbojet technologies have been sparked interest in the scientific humans to investigate from different aspects. Lately, alternative fuels have become the important research issue in mitigating emission impacts [10]. It should be kept in mind that having different disciplines, turbojet engines have been subjected to both the investigation for alternative fuels and improvements of component with innovative technologies. For this aim, turbojet engines have been employed as a reference engine in R&D studies [11, 12]. The engines are analyzed based on their thrust power performance in aircraft applications. Nevertheless, environmental effects of gas turbine engines should be taken into consideration in performing thermodynamics parameters. These parameters are based on internal and external efficiencies in generating thrust power and directly associated with conversion rate of fuel energy. In this context, thermodynamics laws help in calculating performance parameters. It is well known that energy can be conserved whereas entropy tends to rise over time or exergy experiences destruction for real conditions due to irreversibility of processes. The exergy destruction means the existing actual losses in process. Performance evaluation of gas turbine engines are handled with the Brayton cycle. The flow passed through turbojet engine is subjected to important energy degradation in individual components. These degradations could be quantified by entropy production.

There are a number of studies about energy and exergy evaluation regarding turbojet engines [13-15]. Turan [9] scrutinized effects of turbine inlet temperature and centrifugal compressor pressure ratio on exergetic performance of small scaled turbojet at ambient conditions of 9000 m. According to the athor, the overall efficiency of turbojet engine increases from 8.9 % to 10 % due to rising Mach from 0.8 to 0.9. On the other hand, Balli [16] scrutinized exergy and sustainability parameters for turboprop engine. The author stated that the combustor amongst the all components are significant component that leads to lowering the engine efficiency. Its exergy efficiency is 52.51 %. Sohret [17] investigated exergo-sustainability and ecological metrics regarding gas turbine engine. According to the author, ESI of the engine is calculated as 0.40 whereas the ecological function is determined as -8732.21 kW. Balli and Caliskan [18] examined JT15D with thermodynamic and environmental aspects. The authors expressed that the ecological and environmental effect factors of the JT15D are computed to be 5.020 and 4.020. According to the authors, the combustor and low pressure compressor are two that should be focused. Tuzcu et al. [19] performed analyses of energy, environment and enviroeconomic for turbofan engine. The author stated that energy efficiency of turbofan engine is calculated as 19.7 % and CO2 emissions emitting in a day are measured as 358.9 ton CO2/day. Another study about thermodynamic and environmental performances of turbojet engine based on flight conditions was conducted by Sogut [20]. The author expressed that according to flight processes, the mean energy and exergy efficiency of turbojet engine considered are 38 % and 23.04 %, respectively.

Several researches have been reported in the literature concerning energy optimization of gas turbine engine. Silva et al. [21] conducted the study about performance optimization of gas turbine so as to maximize thrust for the same fuel consumption and to minimize turbine blade temperature. They expressed that inlet and outlet geometry parameters can be modified to reduce fuel and decreasing of turbine blade temperature also leads to reduce fuel flow while keeping nominal thrust value. Choi and Sung [22] investigated optimum ranges of several design parameters of small-scaled turbofan engine for maximum net thrust and minimum SFC employing particle swarm optimization. The authors expressed that SFC of the FJ44-2C turbofan engine could be decreased up to 11 % by optimum variables of BPR and HPC PR. Najjar and Balawneh [23] studied about optimization of specific thrust and specific fuel consumption for turbojet engine using General Algebraic Modeling System (GAMS). The authors found that decreasing TIT by 10 % leads to increase 6.8 % in SFC and 6.7 % in ST. At the same way, decreasing CPR by 10% leads to rise 1.34 % in SFC and decrease 0.022 % in ST. Patel et al. [24] examined many-objective optimization of performance parameters including efficiency, thrust, and fuel consumption. According to the applied methods, optimum

Table 1. Literature methodology review about gas turbine engines

Gas turbine engine	Methodology	References
Turbojet	Energy/Exergy	[9]
Turboprop	Energy/Exergy	[16]
Turbojet	Energy/Exergy	[17]
Turbofan	Energy/Exergy	[18]
Turbofan	Energy/Environment/ Enviroeconomic	[19]
Turbojet	Energy/Exergy	[20]
Turbojet	Energy/optimization	[21]
Turbofan	Performance/ optimization	[22]
Turbojet	Performance/ optimization	[23]
Turbojet	Performance/ optimization	[24]
Turbojet	Energy/Exergy/ optimization	[25]
Turbojet with afterburner	Energy/Exergy	[13]
Turbojet with afterburner	Energy/Exergy	[14]
Turbojet with afterburner	Energy/Exergy/ optimization	Present study

results were found as 16.2 g/kN.s for SFC and 1166 N.s/kg for ST.On the other hand, Ekrataleshian et al. [25] were analyzed energetic and exergetic optimization for turbojet engine. The authors stated that optimum thermal efficiency regarding turbojet is computed 65.86% and 66.95% by TOPSIS and LINMAP, respectively. Table 1 presents literature methodology review about gas turbine engines. According to Table 1, the difference of the current study is that optimization method for energy and exergy metrics is implemented to turbojet with afterburner.

It is well known that different design parameters such as compressor pressure ratio and turbine inlet temperature highly affect the performance outputs such as specific thrust, specific fuel consumption and overall efficiency regarding gas turbine engines. Considering optimization of performance parameters for gas turbine engine, optimization of energy and exergy parameters of an afterburning turbojet engine has not been well addressed in the open literature. The main originalities for the current study are to show the differences between military and afterburner modes and to help in finding optimum design parameters leading minimum environmental impact. Thanks to the specific code developed in the current study, both performance and exergetic parameters regarding TJEAB could be scrutinized so as to find optimum design parameters. The engine with optimum parameters allows military aircraft to extend its range or endurance.

This paper differs substantially in extent from previous papers in a number of aspects. Firstly, in this study, energy and exergo-sustainability indexes of the afterburning turbojet engine at military mode and afterburner mode are parametrically are investigated by encoding parametric cycle equations regarding TJEAB. The reason why exergo-sustainability parameters are involved in this study is that these parameters help in understanding design variables that lead to the lowest and the highest environmental-sustainability. Secondly, effects of CPR and TIT on these parameters were scrutinized. Thirdly, optimization code based on parametric cycle equations of TJEAB was developed at MATLAB environment. Finally, optimization of five parameters that consist of SFC, overall efficiency, exergy efficiency, EEF and ESI was carried out at mentioned-above conditions. The basic contributions of this study can be presented below:

- To perform parametric cycle analysis of an afterburning turbojet engine
- To investigate effects of design variables on performance parameters such as specific fuel consumption, specific thrust and overall efficiency for TJEAB
- To search how selected design parameters affects exergetic indicators such as exergy efficiency, environmental effect factor and exergetic sustainability index
- To carry out optimization of performance and exergo-sustainability parameters at mentioned-above condition.

SYSTEM DESCRIPTION

The gas turbine engines have been improved and enlarged since its first successful production in the 1930s. Gas turbine engine are firstly invented from the idea of impulse and reacting air tubes [26]. Developed previously for military needs, turbojet engines have been customized for unmanned aerial vehicles (UAVs) applications. Besides, many test applications include these turbojet engines so as to investigate different innovation technologies on them.

As mentioned before, high interest in the usage of unmanned aircraft leads to increase the usage areas of turbojet engines [12]. In this regard, several new fields of applications are aroused. Exceeding speed of sound, UAVs includes turbojet engines for thrust production. For this aim, there are a number of turbojet engines having different thrust magnitudes for UAV applications. On the other hand, difference between a reciprocating engine and a turbojet engine is directly related to generated power. Namely, turbojet engine obtains this power with repellent nozzles. Besides, pressure ratio of compressor without turbulence or disturbed airflow affects the engine performance whereas effect of turbine intake on the forward speed is of high importance. It is well known that on the contrary to turbofan engine, turbojet engines generate high thrust from exhaust gases with high speed. The basic working principle of turbojet engine are associated with on thermodynamic principles of the Brayton cycle. Firstly, the air compressor draws surrounding air so as to gradually pressurize it. Achievement of this process varies depending on isentropic efficiency of compressor [27]. After that, the compressed air continues to pass the combustor in which the combustion event happens spraying fuel. There is generally the pressure drop in the combustor. For real conditions, isobaric condition could not exactly occur. The combustion gases with high temperature introduce the turbine that generates the work so as to drive the compressor. In this regard, turbine inlet temperature is of high importance due to affecting thermal efficiency. It is well known that TIT depends on metallurgical limits of the turbine. Military mode means that the turbojet operates at relatively low fuel consumption in where fuel is only burnt the combustor. However, afterburner mode means that the engine has the additionally thrust thanks to afterburner module in where the gases coming from turbine is burnt again in case of the important flight misssions such as the combat [28]. In the current study, the conceptual afterburning turbojet engine consists of axial compressor, combustor, turbine and one spool. It is illustrated in Fig.1.

Moreover, Fig.2 (a) shows the station number of individual components whereas Fig.2 (b) demonstrates T-s diagram regarding a typical turbojet engine with afterburner for real cycle.

PERFORMANCE AND ENERGY EQUATIONS FOR TJEAB

Considering parametric cycle equations of the afterburning turbojet engine, the outputs of some performance parameters such as specific fuel consumption (SFC), specific thrust (ST) as well as internal and external efficiencies of TJEAB are estimated under military and afterburner modes. As a matter of fact, the first aim of this study is to perform performance analysis for TJEAB at sea level condition-zero Mach.

Considering each component as control volume at steady-state, propulsion system could be modelled by applying mass and energy governing equations. When the working flow undergoes these equations at individual components, variation of enthalpy, heat transfer and work rates can be estimated. In this section, the governing equations regarding each component of TJEAB are presented. Table 2 presents input variables for parametric cycle analysis of the conceptual TJEAB.

Parametric Cycle Equations

Firstly, parametric cycle equations for compressor are given between eqs.1-6 [28, 30]. With helps of these equations, pressure and temperature of compressor outlet could be calculated. Besides, polytropic efficiency and work rate for compressor could be estimated. In current study, it is considered that specific heat depends on temperature.

$$\dot{m}_2 = \dot{m}_3 \tag{1}$$

$$P_{t,3} = \pi_{comp.} P_{t,3} \tag{2}$$

$$T_3 = T_2\left[1 + \frac{1}{\eta_{comp.}}\left(\pi_{comp.}^{(\gamma c-1)/\gamma c} - 1\right)\right] \tag{3}$$

$$\eta_{comp} = \frac{h_{t3s} - h_{t2}}{h_{t3} - h_{t2}} \tag{4}$$

$$\dot{W}_{comp.} = \dot{m}_3 Cp_{air}\left(T_3 - T_2\right) \tag{5}$$

$$Cp_{air}(T) = 1.04841 - 0.000383719(T) + \frac{9.45378(T^2)}{10^7} - \frac{5.49031(T^3)}{10^{10}} + \frac{7.92981(T^4)}{10^{14}} \tag{6}$$

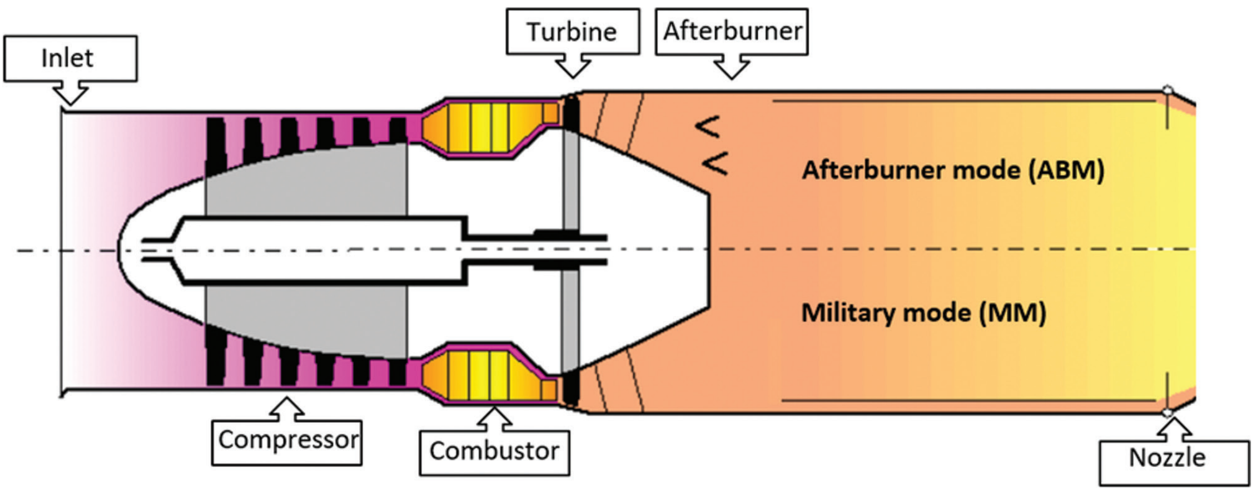

Figure 1. Schematic illustration of afterburning turbojet engine [29].

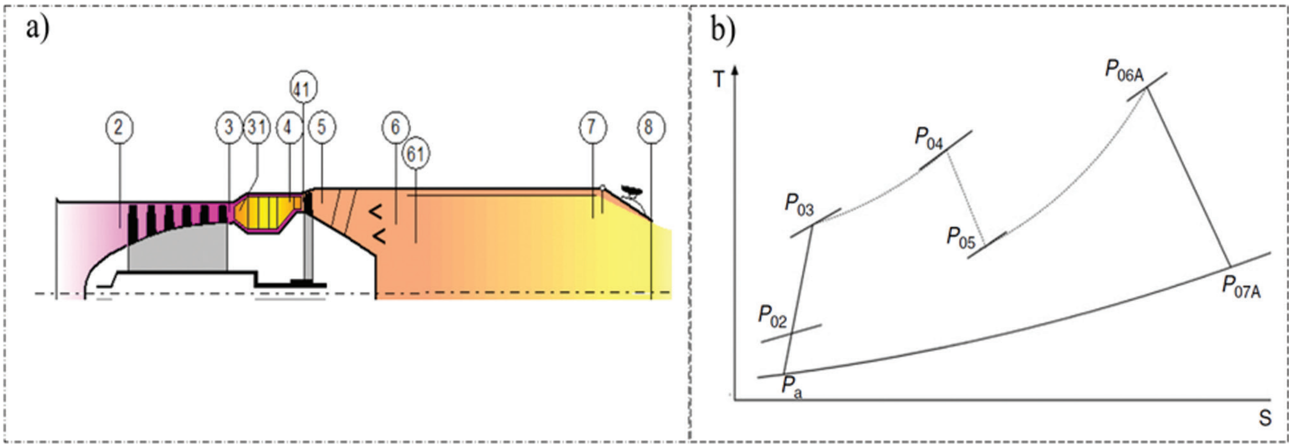

Figure 2. Demonstration of the station number of components and T-s diagram for typical turbojet with afterburner [28, 29]

Table 2. Design variables of turbojet with afterburner (TJEAB) and its components

Parameter	Value
Air mass flow (kg/s)	1
Diffuser pressure loss	0.95
Specific heat value (cold air) (kJ/kgK)	1.0048
Specific heat ratio (for compressor)	1.4
Compressor pressure ratio	7
Compressor isentropic efficiency	0.89
CC efficiency	0.98
Fuel lower heating value (kJ/kg)	42800
Turbine inlet temperature (K)	1250
Turbine isentropic efficiency	0.91
Specific heat ratio (for turbine)	1.3
Afterburner outlet temperature (K)	1900
AB efficiency	0.96
Specific heat value (hot gas) (kJ/kgK)	1.2
Shaft mechanic efficiency	0.98
Static pressure ratio at the exhaust	0.9
Ambient conditions	
Temperature (sea level) (K)	288.15
Pressure (sea level) (kPa)	101.325

Combustor

On the other hand, energy equations for the combustor are presented between Eqs.7-10 [28, 30]. After applying thermodynamics relations, fuel-air ratio and pressure of the combustor outlet could be computed.

$$\dot{m}_4 = \dot{m}_3 + \dot{m}_f \tag{7}$$

$$\dot{m}_{03} c_{p,03} T_{03} + \eta_{cc} m_f Q_{LHV} = \dot{m}_{03} c_{p,04} T_{04} \tag{8}$$

$$f = \frac{\left(Cp_4 T_4 - Cp_c T_3\right)}{\eta_b Q_{LHV} - Cp_4 T_4} \tag{9}$$

$$P_{t,04} = \pi_{cc} P_{t,03} \tag{10}$$

Turbine

As for turbine, when it is subjected to parametric cycle equations, temperature and pressure of the turbine outlet could be found. Also, valuable information is obtained about work rate and polytropic efficiency of turbine. It is well known that turbine work rate should be satisfied that of compressor. Otherwise, parametric cycle could not be completed. In this regard, polytropic efficiency and work rate for turbine could be predicted by eqs.13-14 [28, 30].

$$\dot{m}_4 = \dot{m}_5 \tag{11}$$

$$\pi_{turb} = \left[1 - \frac{1}{\eta_{turb}}\left(1 - \frac{T_5}{T_4}\right)\right]^{\gamma_h/(\gamma_h - 1)} \tag{12}$$

$$\eta_{turb} = \frac{h_{t4} - h_{t4}}{h_{t4} - h_{t5s}} \tag{13}$$

$$\dot{W}_{turb} = \dot{m}_4\left(h_4 - h_5\right) \tag{14}$$

$$C_{p,gas}(T) = 0.9910 + \frac{3.606(T)}{10^5} + \frac{1.552(T^2)}{10^7} - \frac{6.76(T^3)}{10^{11}} \tag{15}$$

Afterburner

If afterburner is inactive, Eqs.16-17 are valid whereas for active afterburner, eqs.18-19 are deployed. Thus, fuel-to air ratio for afterburner is calculated.

If afterburner is inactive

$$P_6 = P_5 - \Delta P_{ab} \quad (16)$$

$$T_6 = T_5 \quad (17)$$

If afterburner is active

$$\dot{m}_{06} c_{p,06} T_{06} + \eta_{ab} \dot{m}_{fab} Q_{LHV} = m_{07} c_{p,07} T_{07} \quad (18)$$

$$f_{ab} = \frac{(1+f)(Cp_{6A} T_{06A} - Cp_5 T_5)}{\eta_{ab} Q_{LHV} - Cp_{6A} T_{06A}} \quad (19)$$

Exhaust Nozzle

As for the nozzle of the TJEAB, this section provides in calculating exhaust velocity. In this context, computation of exhaust velocity varies depending on flow condition at nozzle. Eqs.20-21 express relations for unchoked flow whereas eqs.22-23 represent relations of choked flow [28, 30].

If afterburner is active and nozzle is unchoked

$$\frac{P_{6A}}{P_c} = \frac{1}{\left[1 - (1/\eta_n)(\gamma_h - 1)/(\gamma_h - 1)\right]^{\gamma_h/(\gamma_h - 1)}} \quad (20)$$

$$V_{7ab} = \sqrt{2Cp_h \eta_n T_{6A}\left[1 - \left(\frac{P_{amb}}{P_{6A}}\right)^{\gamma_h/(\gamma_h - 1)}\right]} \quad (21)$$

If nozzle is choked

$$\frac{T_{6A}}{T_7} = \left(\frac{\gamma_h + 1}{2}\right) \quad (22)$$

$$V_{7ab} = \sqrt{\gamma_h R T_7} \quad (23)$$

Performance Parameters of TJEAB

The performance analysis for the propulsion system carried out according to parametric cycle equations and thermodynamics relations. Considering a control volume (CV) for an TJEAB model illustrated in Fig 3, thrust force equation of the TJEAB model can be achieved integrating basic conservation laws of mass and momentum. CV is placed between the inlet (1) and exhaust (2) of the engine. There is inlet area (A_i) at where air enters to the engine and exhaust area (A_e) at where gases leave from the engine. For thrust relation with afterburner, general equation is expressed in eq.24.

On the other hand, Fig. 3 depicts power equations acting on control volume (the engine). Based on these relations, propulsive efficiency, thermal efficiency and overall efficiency are calculated. These are expressed in eqs.25-27, respectively [28].

$$\frac{T}{\dot{m}_a} = \left[(1 + f + f_{ab})V_e - V_i\right] + \frac{A_e}{\dot{m}_a}(P_e - P_i) \quad (24)$$

where $T/\dot{m}_a$ is specific thrust whereas f and f_{ab} denote fuel flow for combustor and afterburner, respectively. Also, A_e and P_e represent exit area and pressure of the exhaust

$$\eta_p = \frac{V_i T}{V_i T + (1/2)\dot{m}_e (V_e - V_i)^2} \quad (25)$$

where η_p denote propulsive efficiency. Besides, $\dot{m}_e$ consists of air and fuel mass flows.

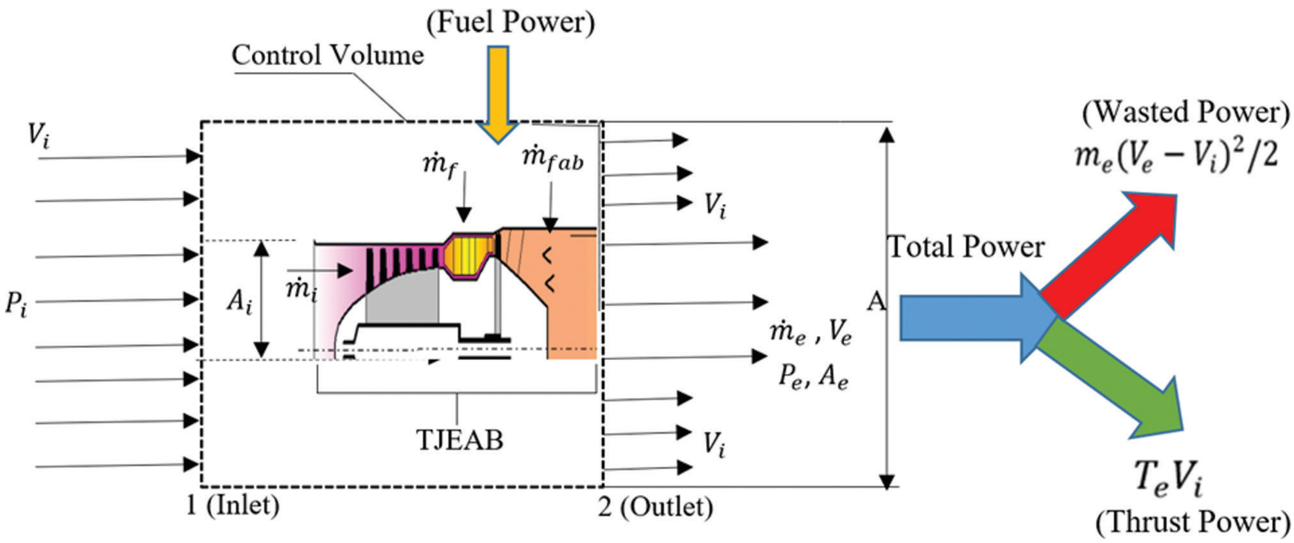

Figure 3. Representative control volume for forces acting on turbojet with afterburner and power distribution.

$$\eta_{th} = \frac{V_i T + (1/2)\dot{m}_a (1+f)(V_e - V_i)^2}{\dot{m}_f Q_{LHV}} \quad (26)$$

where η_{th} denote thermal efficiency. Q_{LHV} is lower heating value of kerosene fuel.

$$\eta_o = \eta_p * \eta_{th} \quad (27)$$

Exergetic and Exergo-Sustainability Equations

For propulsion systems, exergy analysis has been mainly preferred so as to quantify potential improvements. Namely, it could enable information about location and magnitudes of irreversibility occurred in each component. Irreversibility can be defined as difference the actual work and the reversible work. In this regard, this difference refers to exergy destruction [31]. Moreover, irreversibility means wasted power or the lost opportunity to generate useful work. The less irreversibility leads to increase the work generated and to decrease the work consumed. Namely, exergy is defined as the maximum produced work (for turbine) or minimum consumed work (for compressor) according to the dead ambient condition [32]. This concept could be obtained from equations of energy and entropy. Exergy indicates thermodynamic weaknesses originated from the irreversibility in each component. Thermal losses in components adversely affect expected efficiency. In this context, the improvement potential for individual components can be determined as a strategic target in the design and innovation studies.

Irreversibility in the propulsion system directly results in decreasing thermal performance and thereby in increasing fuel consumption. The higher fuel consumption means the higher environmental impact from the engine exhaust. Environmental impacts in fossil-derived propulsion systems could be quantified by different methods. Exergo-sustainability parameters such as environmental effect factor, exergetic sustainability index indicate environmental impact in terms of irreversibility.

Physical, chemical, potential and kinetic exergy represent main components of general exergy equation for thermal system. Generally, kinetic and potential exergies are omitted in calculating exergy value of flow due to being their relatively small magnitude. This is expressed as follows [33]:

$$\dot{E}x = \dot{E}x^{PH} + \dot{E}x^{CH} + \dot{E}x^{PT} + \dot{E}x^{KN} \quad (28)$$

The physical exergy arises from the difference of temperature and pressure of the system with respect to the environment conditions [34].

$$^{PH} = C_{p,a}\left(T - T_0 - T_0 \ln\frac{T}{T_0}\right) + R_a T_0 \ln\frac{P}{P_0} \quad (29)$$

Chemical exergy occurs due to the deviation of chemical composition in the combustor with respect to ambient conditions. Eq.30 is employed in computing exergy flow of the fuel. γ_f denotes for the ratio of exergy flow of the fuel. It is considered as 1.06 for natural gas [34].

$$\frac{\varepsilon_{ch,f}}{LHV} = \gamma_f = 1.04224 + 0.011925\frac{b}{a} - \frac{0.042}{a} \quad (30)$$

After the combustion in the combustor, the exergy for the product of combustion gas is calculated using eq.31

$$\overline{ex}_{ch,i} = \sum x_i \overline{ex}_{ch,i} + \bar{R}T_0 \sum x_i \ln x_i \quad (31)$$

where the subscript i represents the type of air fraction considered, x indicates the molar fraction of the air and $\overline{ex}_{ch,i}$ is the standard chemical exergy of each type of air fraction.

The exergy destruction of each component could be figured out by taking difference between input and output exergy flow rates. It is well known that exergy flow undergoes diminishment after each process.

$$\dot{E}x_{dest} = \sum\left(1 - \frac{T_0}{T_k}\right)\dot{Q}_k - \dot{W} + \sum_{in}\dot{E}x_{in} - \sum_{out}\dot{E}x_{out} \quad (32)$$

Considering exergetic component acting on the whole engine, Fig.4 indicates these exergetic components for general exergy balance. According to this, fuel exergy is provided to the engine, exergy destruction, exergy of exhaust gas and exergy loss is extracted from the engine.

Based on eqs.33-37, for the whole engine, it could be addressed to exergo-sustainability parameters which are exergy efficiency, environmental effect factor and exergetic sustainability index. Total inlet exergy term incorporates two components. These are expressed as total useful exergy, total waste exergy. To balance exergy inputs and outputs, general expression for the TJEAB can be presented [35].

$$\sum \dot{E}x_{in}^{TJEAB} = \sum \dot{E}x_{out}^{TJEAB} + \sum \dot{E}x_{dest}^{TJEAB} \quad (33)$$

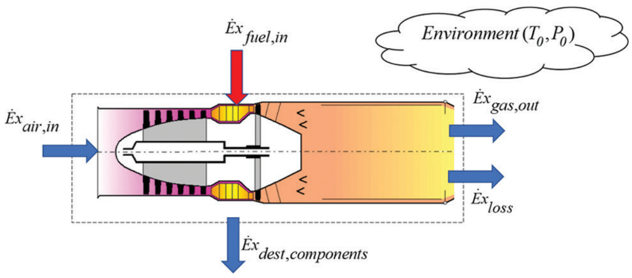

Figure 4. Representative control volume for general exergy inputs and outputs for turbojet with afterburner.

$$\sum \dot{E}x_{in}^{TJEAB} = \dot{E}x_{fuel,ch} + Ex_{02} \quad (34)$$

$$\sum \dot{E}x_{out}^{TJEAB} = \sum \dot{E}x_{useful}^{TJEAB} + \sum \dot{E}x_{waste}^{TJEAB} \quad (35)$$

The specific useful exergy for the TJEAB means multiplication of engine inlet velocity with specific thrust. It is presented as below:

$$\sum \dot{E}x_{useful}^{TJEAB} = \left(Specific\,thrust\right).\left(True\;Air\;Speed\right) \quad (36)$$

$$\sum \dot{E}x_{dest}^{TJEAB} = \sum \dot{E}x_{in} - \sum \dot{E}x_{out} \quad (37)$$

Exergy Efficiency

Energy and exergy analysis are applied to each component so as to calculate which components that enjoy minimum and maximum efficiency

One method to calculate exergy efficiency for the whole engine is that thrust power (useful exergy output) is divided by the total exergy input [35].

$$\eta_{ex}^{TJEAB} = \sum \dot{E}x_{useful}^{TJEAB} \Big/ \sum \dot{E}x_{in}^{TJEAB} = \left(ST * V_{inlet}\right) / \begin{pmatrix} Ex_{02} + \\ Ex_{fuel,ch} \end{pmatrix} \quad (38)$$

Environmental Effect Factor

Environmental effect factor of the TJEAB is of high significance in terms of determining environmental impact. Namely, it shows extent of the damage of the engine to the environment. It is well known that this damage arises from exergy loss and exergy destruction. This indicator could be predicted as ratio of wasted exergy ratio to total exergy efficiency. Besides, it could be written as following expression [35, 36].

$$f_{eef}^{TJEAB} = r_{we}^{TJEAB} \big/ \eta_{ex}^{TJEAB} \quad (39)$$

Exergetic Sustainability Index

Being most beneficial indicators, exergetic sustainability index is presented in this section. This indicator could be figured out by dividing one to environmental effect factor. Also, ESI ranges between 0 and 1. It is desired that this index approaches to 1. This parameter is presented as following [35, 36].

$$\theta_{esi}^{TJEAB} = 1 \big/ f_{eef}^{TJEAB} \quad (40)$$

GENETIC ALGORITHM FOR THE AFTERBURNING TURBOJET-ENGINE PARAMETERS

Optimizing linear or nonlinear models becomes possible using genetic algorithm (GA) technique [37]. Namely, based on natural genetics and selection, GAs represent a robust optimization paradigm employed for general-purpose [38]. Initially, a random population for an appropriate size is chosen in GA. Several inputs or variables constitute a population. The size of population is significant due to affecting the output. Chromosome using in GA denotes the related binary code for each input and involves several bits that consist of 0 and 1 values [39]. The main aim is to obtain the best solution by means of the binary codes. It becomes possible employing GA operators such as crossover and mutation. In this context, some of the chromosomes are subjected to these processes thorough each iteration. Determination of the number of chromosomes as well as the bits of each chromosome is important issue not to rise in the duration of solution. Otherwise, valuable outputs could be removed before reproduction process. After the new outputs are sorted from best to worse and the best outputs are substituted by some of the worse ones, the reproduction process is to be accomplished. Thus, first iteration is completed. Subsequent iterations in GA provide to find the best solution employing the reproduction processes.

The program based on GA developed for current study incorporates several steps. As a first step, input parameters for parametric cycle equations are introduced to program. Meanwhile, the number of population and iteration as well as crossover and mutation ratios are determined. As a second step, design variables of TJEAB as the chromosomes and objective function are defined. At background of the process, the chromosomes are sorted to the values of the actual count of each chromosome. Thus, chromosomes having maximum actual count substitute ones having zero value of actual counts. As a three step, process of crossover and mutation are implemented. As a final step, the output which enjoys the best solution with respect to objective function is recorded at end of first iteration. It should be kept in mind that five objective functions are determined. These are SFC, overall efficiency, exergy efficiency, EEF and ESI. Fig.5 represents flowchart about optimization of parametric cycle analysis for TJEAB. Namely, it summarizes mentioned-above process steps. Moreover, Table 3 presents design variables ranges and input values for GA.

RESULTS AND DISCUSSION

This study incorporates performance evaluation and exergo-sustainability analysis for the conceptual TJEAB at military mode and afterburner mode. Besides, based on this analysis, investigation of performance parameters (SFC and overall efficiency) and exergetic parameters (exergy efficiency, EEF and ESI) were performed based on genetic algorithm approach at sea level-zero Mach. The magnitude of performance indicators was quantified by energy analysis. To encode parametric cycle equations regarding the TJEAB model, MATLAB software was preferred. Based on this code, pressure and temperature values of the working

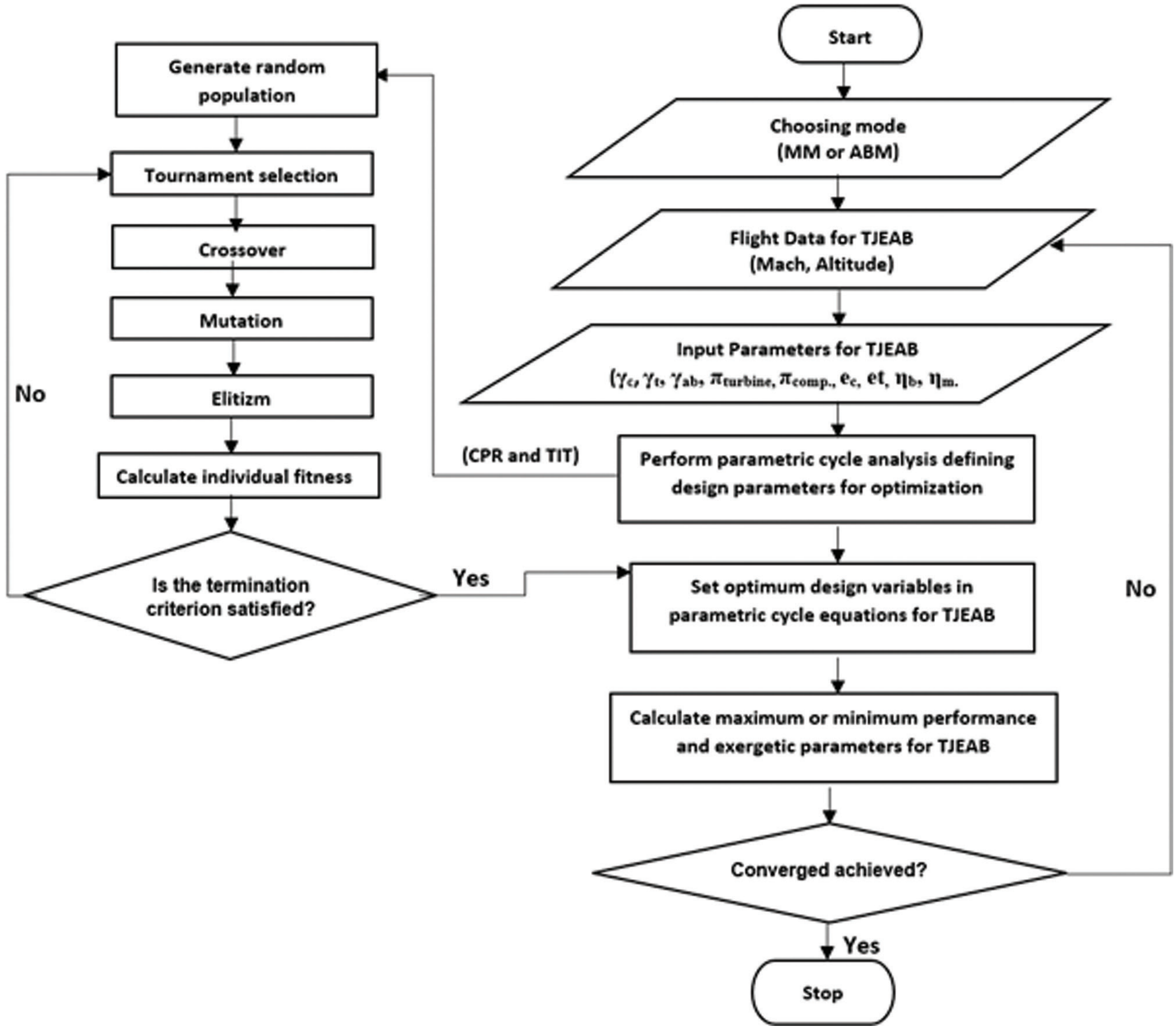

Figure 5. Flowchart optimization of parametric cycle analysis for turbojet with afterburner.

flow after each process could be determined for both modes. Moreover, for the TJEAB model, impacts of design parameters on performance and exergetic parameters were scrutinized to find effective parameters for optimization.

Considering performance parameters, Figs.6-8 illustrate overall efficiency, specific fuel consumption and specific thrust regarding TJEAB at sea level-zero Mach. Figs. 9-11 present findings of exergy efficiency, ESI and EEF with respect to CPR and TIT. Figs.12-13 depict specific power values according to CPR and TIT. After that point, it was addressed to optimization of mentioned-above parameters by means of Figs.14-18 for sea level condition-zero Mach.

Fig.6 demonstrates specific thrust value of TJEAB with respect to TIT and CPR at MM and ABM. As can be seen in Fig.6, the rising of TIT and CPR affects favourably specific thrust for both MM and ABM. Firstly, considering military mode, at constant TIT of 1250 K and changing CPR ranges from 4 to 11, ST increases from 701.73 N.s/kg to 774.01 N.s/kg. At the same way, for constant CPR of 7 and TIT between 1150 K and 1550 K, ST changes between 691.95 N.s/kg and 934.24 N.s/kg. Secondly, according to afterburner mode, ST is found to be range from 948.32 N.s/kg to 1127.2 N.s/kg at constant TIT of 1250 K and CPR ranging 4 and 11. Likewise, ST resides between 1027.1 N.s/kg and 1150 N.s/kg at constant CPR of 7 and TIT changing 1150 K and 1550 K.

In Fig.7, SFC surface is plotted against TIT and CPR at MM and ABM. SFC is observed to be lower at MM in comparison with ABM. According to Fig.7, increasing of TIT leads to an important increase in SFC value whereas the same case does not hold for afterburner mode. Namely, SFC is favourably affected from increase in TIT at ABM in

Table 3. GA input values and ranges of the design parameters

GA parameters	
Encoding type	Binary
Population size	100
Selection operator	Roulette-wheel
Crossover operator	Two-point
Mutation operator	Uniform
Crossover rate	0.85
Mutation rate	0.05
The Design variables	**Range**
Turbine inlet temperature	1150< TIT <1550
Compressor pressure ratio	4< CPR <11

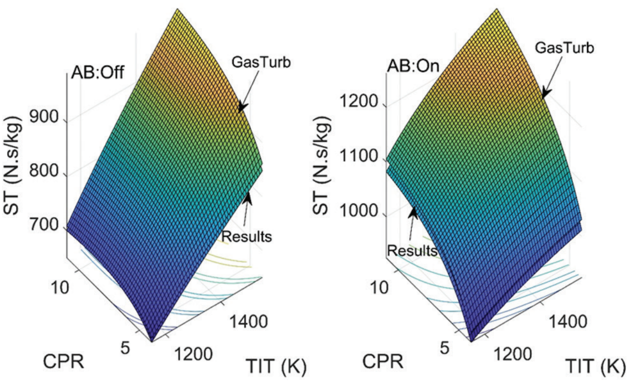

Figure 6. Variation of specific thrust versus CPR and TIT at military and afterburner modes.

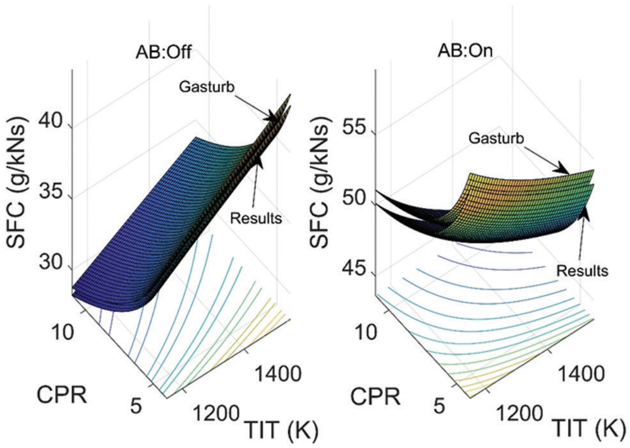

Figure 7. Variation of SFC versus CPR and TIT at military and afterburner modes.

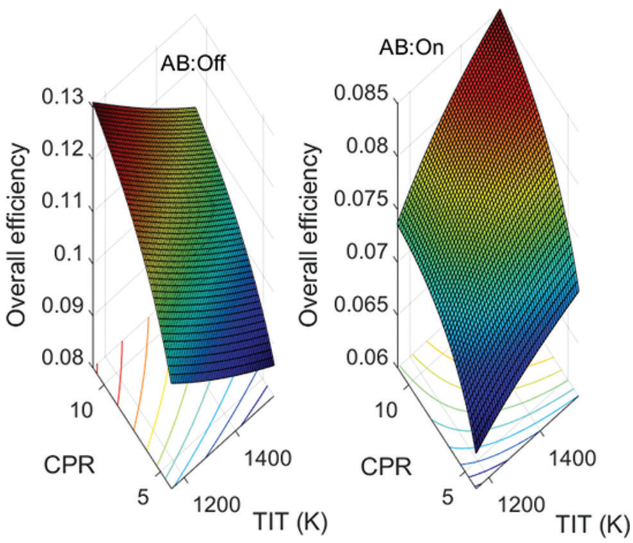

Figure 8. Variation of overall efficiency versus CPR and TIT at military and afterburner modes.

terms of engine performance. In this context, firstly focusing on military mode, at constant TIT of 1250 K, SFC decreases from 38.97 g/kN.s to 29.79 g/kN.s with increasing CPR from 4 to 11. Moreover, at constant CPR of 7 and the rising TIT from 1150 K to 1550 K, SFC is estimated to be in the range of 31.54 g/kN.s and 36.9 g/kN.s. As for afterburner mode, at constant TIT of 1250 K, SFC diminishes from 56.97 g/kN.s to 48.1 g/kN.s with increasing CPR from 4 to 11. Furthermore, at constant CPR of 7 and TIT ranging from 1150 K to 1150 K, SFC changes between 52.77 g/kN.s and 46.88 g/kN.s.

As a function of TIT and CPR, Fig. 8 presents the variations of overall efficiency regarding TJEAB. It is clear from Fig.8 that rising of TIT does not same manner effects on overall efficiency for MM and ABM. In other words, it means that the higher is the TIT, the lower the overall efficiency at MM, but the higher the overall efficiency at ABM. In this regard, at military mode, overall efficiency increases from 9.59 % to 12.5 % at constant TIT of 1250 K and the rising CPR from 4 to 11. Moreover, it diminishes from 11.85 % to 10.13 % at constant CPR of 7 and the changing TIT between 1150 K and 1550 K. As for ABM, overall efficiency experiences the increase from 6.56 % to 7.77 % due to increasing CPR from 4 to 11 at constant TIT of 1250 K whereas it increases from 7.1 % to 7.97 % at TIT ranging between 1150 K and 1550 K and constant 7 of CPR.

Fig.9 displays exergy efficiency of whole TJEAB as a function of CPR and TIT. According to this, exergy efficiency increases with CPR and TIT for MM and ABM. Compared to afterburner mode, exergy efficiency appears higher at military mode. Considering constant 1250 K of TIT and changing compressor pressure ratio ranges between 4 and 11, exergy efficiency of TJEAB changes between 17.98 % and 27.32 % at MM whereas it changes between 12.91 % and 19.1 % at ABM. On the other hand, at

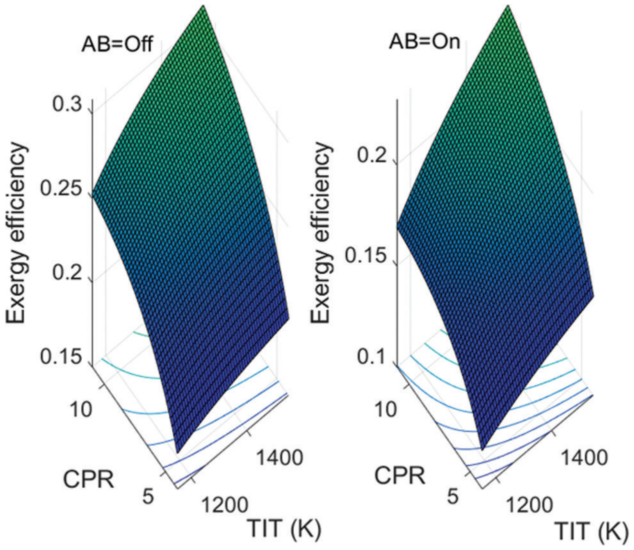

Figure 9. Variation of exergy efficiency versus CPR and TIT at military and afterburner modes.

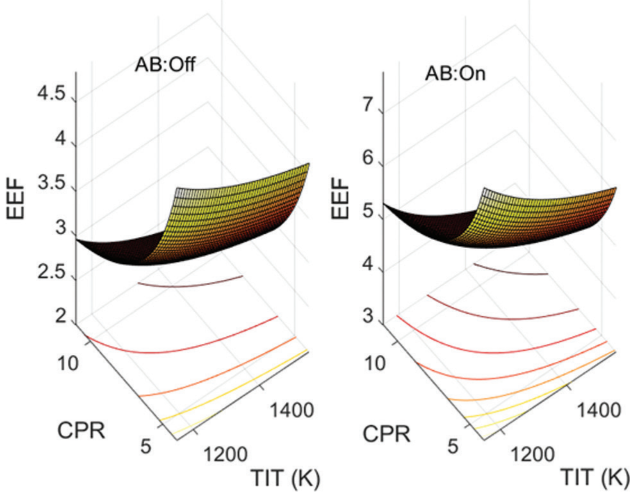

Figure 10. EEF surface according to CPR and TIT at military and afterburner modes.

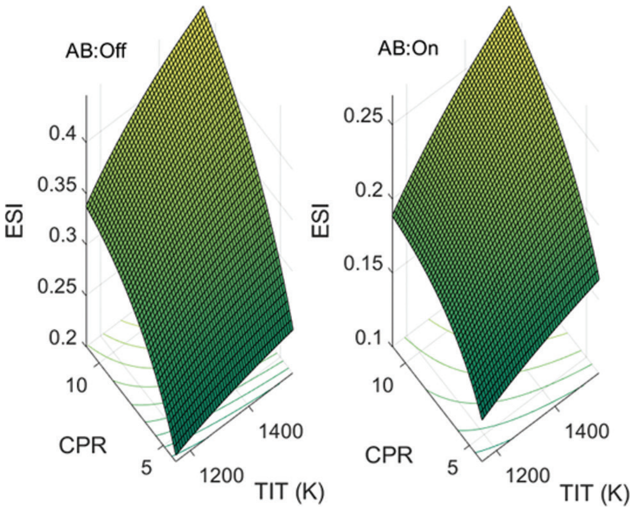

Figure 11. ESI surface according to CPR and TIT at MM and ABM.

constant 7 of CPR and TIT between 1150 K-1550 K, exergy efficiency of TJEAB is estimated to be in the range of 22.57 % and 26.45 % at MM and to be in the range of 15.48 % and 20 % at ABM.

Compared exergy efficiency findings with overall efficiency, exergy efficiency of TJEAB is calculated higher. Also, TIT leads to decrease energy efficiency at MM. The average overall efficiency decreases from 13.47 % to 11.91 % whereas exergy efficiency increases from 26.27 % to 31.03 % due to rising TIT. Considering afterburner mode, overall efficiency raises from 7.47 % to 8.44 % while exergy efficiency increases from 17.54 % to 22.84 % due to rising TIT. This means that afterburner leads to lowering both energy and exergy efficiency. At 1300 K of TIT and 12 CPR, overall efficiency is calculated 16.39 % higher at MM and 12.52 % higher at ABM than for exergy efficiency of TJEAB.

Fig. 10 shows environmental effect factor of TJEAB at MM and ABM. It is expected that EEF value has the higher at ABM compared to MM since afterburner fuel flow is involved to TJEAB. Namely, the higher is the fuel flow, the higher the environmental impact. As can be seen in Fig.10, increasing CPR adversely affects EEF. Also, effect of CPR on EEF is higher than TIT for both modes. In this regard, at military mode, EEF decreases from 4.56 to 2.65 at constant TIT of 1250 K and the rising CPR from 4 to 11. Moreover, it diminishes from 3.43 to 2.78 at constant CPR of 7 and the changing TIT between 1150 K and 1550 K. As for ABM, EEF experiences the decrease from 7.14 to 4.63 due to increasing CPR from 4 to 11 at constant TIT of 1250 K whereas it decreases from 5.85 to 4.37 at TIT ranging between 1150 K and 1550 K and constant 7 of CPR. These results mean that optimum design parameters lead to lowering environmental impact compared with baseline. Also, increasing pressure ratio of compressor without stall event could be more feasible instead of rising TIT that results in higher NOx emission.

As for Fig. 11, it illustrates exergetic sustainability index of TJEAB for MM and ABM at sea-level conditions-zero Mach. According to this, there is a similar pattern for variation of ESI at between MM and ABM. Also, effect of CPR on ESI at MM is higher than that of CPR at ABM. Considering Fig.11, at constant CPR of 7 and TIT between 1150 K-1550 K, exergy efficiency of TJEAB is estimated to be in the range of 0.291 and 0.359. On the other hand, at constant TIT of 1250 K and the varying CPR between 4 and 11, ESI is obtained as up to 0.375 from 0.219. As for ABM, ESI experiences the increase from 0.139 to 0.215 due to increasing CPR from 4 to 11 at constant TIT of 1250 K whereas it rises

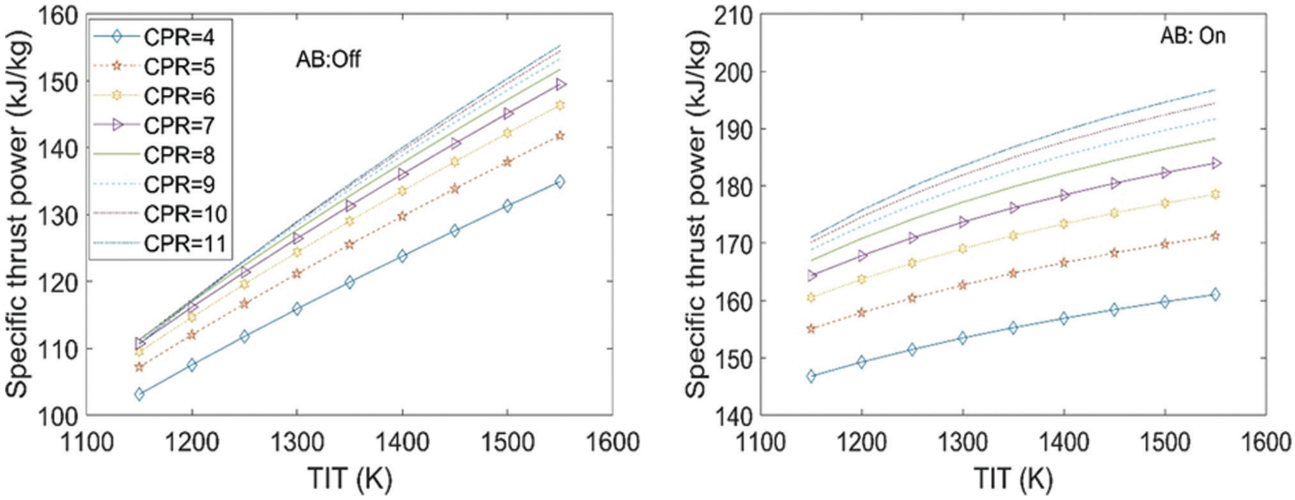

Figure 12. Changement of STP as a function of CPR and TIT at military and afterburner modes.

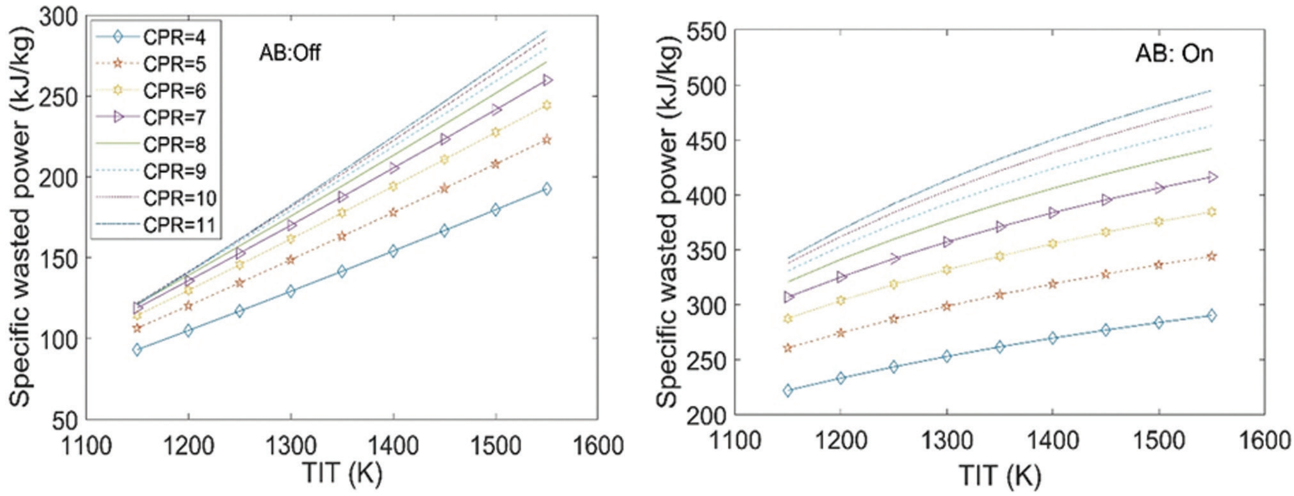

Figure 13. Changement of SWP as a function of CPR and TIT at military and afterburner modes.

from 0.17 to 0.228 at TIT ranging between 1150 K and 1550 K and constant 7 of CPR. According to these findings, sustainability value of the engine could be enhanced with the optimization approach. The higher the ESI of the engine, the higher the environmental sustainability.

Figs.12-13 present specific power values such as thrust and wasted powers at MM and ABM. Fig.12 depicts variation of specific thrust (ST) with respect to CPR and TIT. As expected, ST value is higher at ABM compared to that of MM due to afterburner activation. As can be understood from Fig.12, both CPR and TIT favourably affect specific thrust power at MM and ABM. The highest ST value is calculated as 155.27 kJ/kg for MM and 196.77 kJ/kg for ABM at TIT of 1550 K and CPR of 7. With the increase from 4 to11 in CPR, ST increases from 112.28 kJ/kg to 123.84 kJ/kg whereas ST changes from 118.64 kJ/kg to 149.48 kJ/kg due to increasing TIT from 1150 K to 1550 K. It can be concluded that ST is highly affected from variation of TIT. On the other hand, when focused on afterburner mode, ST varies from 151.73 kJ/kg to 180.36 kJ/kg due to the increase from 4 to 11 in CPR whereas it resides between 167.77 kJ/kg and 184.01 kJ/kg at changing TIT from 1150 K to 1550 K. As a result, effect of TIT on ST at MM is relatively higher compared to ABM.

Fig. 13 illustrates specific wasted power of the TJEAB at MM and ABM. It is well known that to minimize wasted power leads to increase propulsive efficiency, thereby overall efficiency. SWP is calculated higher at ABM since it is directly related to velocity difference between inlet and outlet. Therefore, at ABM, exhaust velocity is the higher due to the combustion reaction of turbine gases in the afterburner. As can be seen in Fig.13, SWP experiences the steepest increase at MM due to variation of TIT. The highest SWP is figured out as 290.53 kJ/kg for MM and 495.02 kJ/kg for

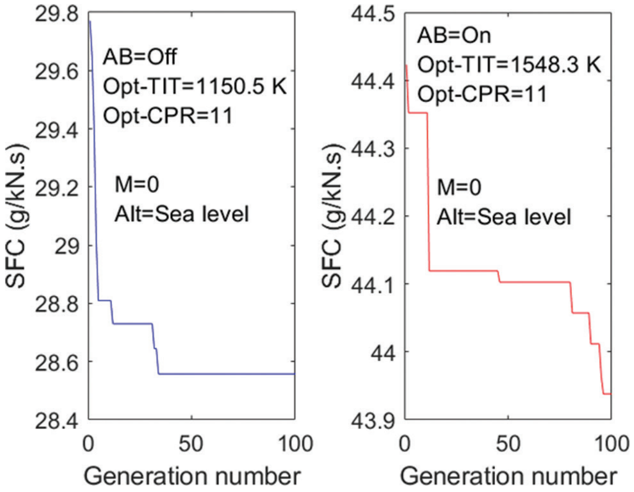

Figure 14. GA optimization of SFC with TIT and CPR variables at military and afterburner modes.

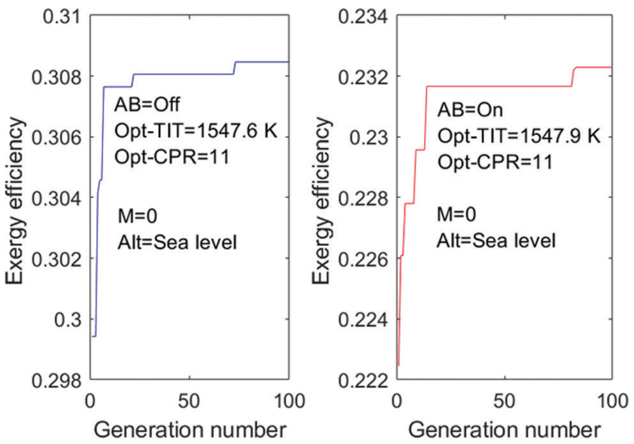

Figure 16. GA optimization of exergy efficiency with TIT and CPR variables at military and afterburner modes.

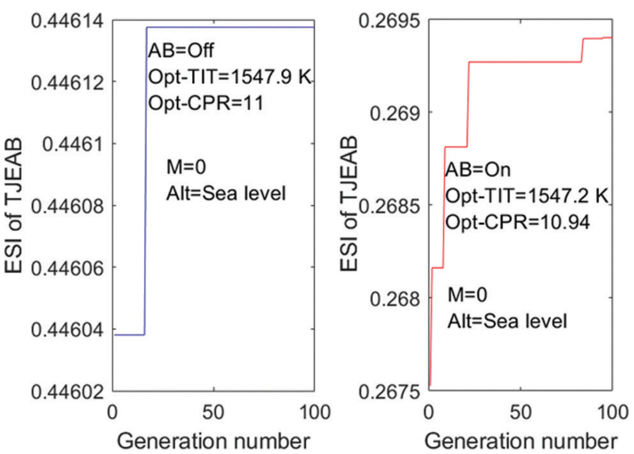

Figure 18. GA optimization of ESI with TIT and CPR variables at military and afterburner modes.

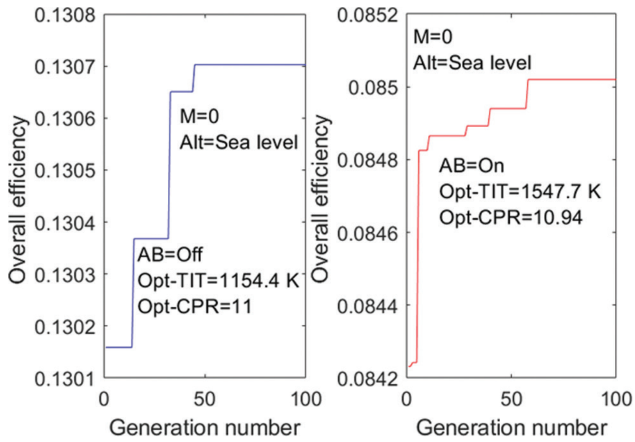

Figure 15. GA optimization of overall efficiency with TIT and CPR variables at military and afterburner modes.

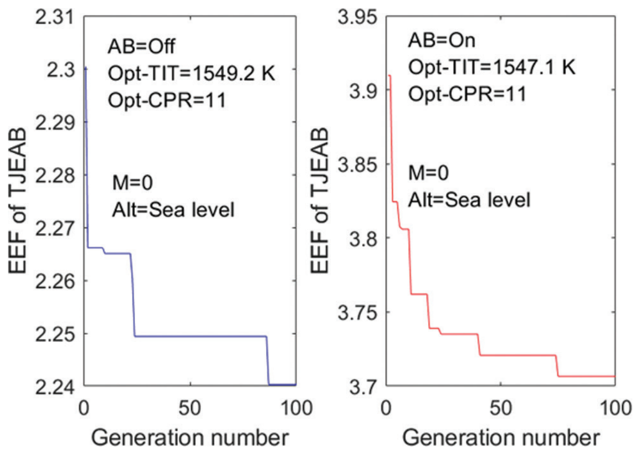

Figure 17. GA optimization of EEF with TIT and CPR variables at military and afterburner modes.

ABM at TIT of 1550 K and CPR of 7. Due to the rising CPR from 4 to11, SWP increases from 118.42 kJ/kg to 163.94 kJ/kg whereas SWP changes from 135.32 kJ/kg to 259.78 kJ/kg due to increasing TIT from 1150 K to 1550 K. It can be highlighted that such as STP, SWP is highly affected from variation of TIT. On the other hand, considering afterburner mode, SWP varies from 244.74 kJ/kg to 394.68 kJ/kg due to the increase from 4 to 11 in CPR whereas it changes between 324.86 kJ/kg and 416.27 kJ/kg at changing TIT from 1150 K to 1550 K. As a result, effect of TIT on SWP at MM is relatively higher compared to ABM.

After that point, Figs.14-18 present optimization results of performance and exergo-sustainability parameters at sea level-zero Mach. In current study, the optimization is carried out with two design variables which are TIT and CPR for both modes. From mentioned-above analyses, optimum values of design parameters can be partially estimated. Thanks to genetic algorithm method, the exact value of these parameters can be determined. For this aim, MATLAB code consisting of performance, exergy equations and optimization relations are developed. In this context, for objective function, SFC and overall efficiency as performance parameters are defined whereas exergy efficiency, EEF and ESI as exergetic parameters are chosen.

As can be understood from Fig.14, minimum SFC value is predicted as 28.59 g/kN.s at MM where optimum values of TIT and CPR are 1150.5 K and 11, respectively. Compared to SFC results without optimization, SFC value is calculated as 32.89 g/kN.s. On the other hand, SFC value is obtained as minimum with 43.95 g/kN.s at ABM where optimum values of TIT and CPR are 1548.3 K and 11, respectively. It should be kept in mind that before applying optimization to TJEAB, SFC value is determined as 50.67 g/kN.s at ABM.

Another parameter to be addressed for performance optimization is overall efficiency. As can be seen in Fig.15, maximum overall efficiency is determined as to be 13.07 % at MM where optimum values of TIT and CPR are 1154.5 K and 11, respectively. Considering afterburner mode for maximum value of this parameter, it is found to be 8.5 % at this mode where optimum values of TIT and CPR are 1547.7 K and 11, respectively. Initial values of overall efficiency for MM and ABM are 11.36 % and 7.38 %, respectively.

Figs.16-18 present optimization findings for exergetic parameters. According to Fig.16, maximum exergy efficiency is estimated as 30.85 % at MM where optimum values of TIT and CPR are 1547.6 K and 11, respectively. When focusing on exergy efficiency outcomes without optimization, its value is determined as 23.9 %. On the other hand, exergy efficiency is obtained as maximum with 23.2 % at ABM where optimum values of TIT and CPR are 1548.3 K and 11, respectively. Bearing in mind that before TJEAB is subjected to optimization, exergy efficiency is determined as 16.9 % at ABM.

Fig.17 addresses optimization of environmental effect factor (EEF) of TJEAB. It is clear from Fig.17 that minimum EEF is determined as to be 2.24 at MM where optimum values of TIT and CPR are 1549.2 K and 11, respectively. Considering afterburner mode for minimum value of this parameter, it is found to be 3.74 at this mode where optimum values of TIT and CPR are 1547.1 K and 11, respectively. Initial values of EEF for MM and ABM are 3.18 and 5.29 respectively.

The final finding for sea level-zero Mach is illustrated about ESI optimization of TJEAB in Fig. 18, According to this, at MM, optimum value of design parameters achieving maximum ESI which is 0.446 are found to be 1547.9 K for TIT and 11 for CPR. Considering afterburner mode, optimum value of design parameters giving maximum ESI which is 0.269 are determined to be 1547.2 K for TIT and 11 for CPR. If optimization tool is not applied to TJEAB parameters, ESI is to be 0.314 at MM and 0.188 at ABM.

CONCLUSIONS

Studying performance and energy optimization of aircraft engine is of high importance so as to help in finding optimum design variables. Especially, since the engine operating inefficient results in increasing fuel consumption, thereby environmental impact, quantifying energy and exergy indexes could show effect of the aeroengine on environment. In this paper, performance and exergy optimization based on parametric cycle equations for the conceptual afterburning turbojet engine at sea level conditions-zero Mach or maximum take-off power. The results of the current study highlight main findings as follows:

- rising of TIT and CPR affects favourably specific thrust for both MM and ABM.
- The increasing of TIT leads to an important increase in SFC value whereas the same case does not hold for afterburner mode. Namely, SFC is favourably affected from increase in TIT at ABM in terms of engine performance.
- Minimum SFC is estimated as 28.59 g/kN.s at MM and 43.95 g/kN.s at ABM where optimum values of TIT and CPR are 1150.6 K and 11, respectively. Compared with baseline, the SFC gain is calculated as 2.92 % lower at MM and 7.76 % lower at ABM.
- Maximum overall efficiency is determined as to be 13.07 % at MM and 8.5 % at ABM. The difference between baseline and optimum values are computed as 0.38 % higher at MM and 0.66 % higher at ABM.
- Maximum exergy efficiency is estimated as 30.85 % at MM and 23.2 % where optimum values of TIT and CPR are 1547.6 K and 11, respectively. Optimization of TJEAB results in computing 2.93 % higher at MM and 3.62 % higher at ABM in comparison with baseline.
- Minimum EEF is determined as to be 2.24 at MM and 3.74 at ABM. Compared with baseline, the EEF difference is calculated as 13.2 % lower at MM and 17.25 % lower at ABM.
- Optimum value of design parameters achieving maximum ESI which are 0.446 at MM and 0.269 at ABM are found to be 1547.9 K for TIT and 11 for CPR.

Considering these findings, increasing of CPR for performance and exergetic improvement of TJEAB becomes beneficial whereas this case does not hold for the increasing of TIT for both modes. However, high TIT is required for enhancement of exergetic performance at both modes. Combining performance and exergetic tools results in novel ways of thinking for the turbojet engine at the cycle design along with different running conditions. It is thought that the current study could become beneficial at the preliminary design phase of similar turbojet engines. For future study, performance and exergy analyses of TJEAB involving flight phases can be performed. Also, multi-objective optimization process with decision making methods can be carried out to reveal trade-off between performance parameters using different design variables.

NOMENCLATURE

A	Area(m^2)
AB	Afterburner
ABM	Afterburner mode
BPR	By-pass ratio
C_p	Specific heat (kJ/(kg.K))
CC	Combustion chamber
CPR	Compressor Pressure Ratio
CV	Control volume
$\dot{E}$	Energy rate (MW)
EN	Exhaust nozzle
EEF	Environmental effect factor
ESI	Exergetic Sustainability Index
Ex	Exergy
GA	Genetic Algorithm
GAMS	General Algebraic Modeling System
h	Altitude (m)
HPC PR	High Pressure Compressor Pressure Ratio
LHV	Lower heat value (kJ/kg)
LINMAP	Linear programming technique for multidimensional analysis of preference
M	Mach number
MM	Military mode
MOHTS	Multi-objective heat transfer search
$\dot{m}$	mass flow rate (kg/s)
P	Pressure(kPa)
R	Specific gas constant (kJ/kg.K)
R & D	Research and Development
S	Specific entropy (kJ/kgK)
SFC	Specific fuel consumption (g/kN.s)
ST	Specific thrust (Ns/kg)
STP	Specific thrust power (kJ/kg)
SWP	Specific wasted power (kJ/kg)
T	Temperature (K)
TIT	Turbine inlet temperature
T	Thrust (kN)
TJEAP	Turbojet with afterburner
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
UAV	Unmanned Aerial Vehicle
Q	Heat transfer rate (MW)
V	Velocity (m/s)
W	Power rate (MW)

Greek letters

ε	Specific Exergy
η	Energy efficiency
π	Pressure ratio
γ	Specific heat constant
Δ	Difference

Subscripts

a	Air
ab	Afterburner
ch	Chemical
comp	Compressor
f	Fuel, fuel-air ratio
g	Gas
gen	Generation
e	Exit, specific energy
c	Cold
h	Hot
in	Inlet
k	kth component
out	Outlet
ph	Physical
t	Total
turb	Turbine
0	Ambient
1,2 ,..k	Station numbers of engine components

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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