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EXERGY ANALYSIS OF AN AIRCRAFT TURBOJET ENGINE

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ABSTRACT

In the present study, the exergy analysis was done on the different sections of the turbojet engine J85-GE-21 in three different flights Mach number (0.4, 0.6 and 0.8). Parametric analysis is carried out based on exergy analysis to see the effects of main cycle parameters on cycle efficiency. In this paper, second law analysis is performed to able to see exergy destruction throughout the turbojet engine. The results show that the greatest exergy loss in the after burner due to its high irreversibility. As the second major exergy loss is in combustion chamber, the optimization of after burner has an important role in reducing the exergy loss of total turbojet engine cycle. Using the small amount of information provided by cabin indicators and writing the computer code, the highest exergy efficiency can be calculated from a specified Mach number (0.4). It's shown from results that mainly based on the operating parameters for 0.6 $<R_{Nozzle}<$ .09, 2700 K < T_6 < 3600 K increase in the after burner temperature the on propulsion efficiency of the cycle increases for both. However, for all nozzles pressure ratio the SFC of the cycle increase by increase in the Mach number of the turbojet engine.

KEYWORDS: turbojet engine, exergy analysis, after burner.

INTRODUCTION

Exergy analysis based on the first and second thermodynamic laws is a significant tool to analyze the energy systems. It also reveals the inefficient thermodynamic processes. Recently, exergy analysis has become a key issue in providing a better understanding of the processes, to quantify sources of inefficiency and to distinguish quality of energy consumption [1, 3]. Kotas [3] and Szargut[4] studies on exergy costs have been provided at conferences by American Association Mechanic Engineers. Similarly, a lot deals of research on exergy analysis have been conducted by Moran [5] analyzing energy, Turan [6] carried out Exergetic effects of some design parameters on the small turbojet engine. They also considered the effect of the Mach number variations and turbine inlet temprature in order to find the exergy destruction in each component of the cycle. Flight Mach number significantly affects the energetic efficiency of the engine. Bejan [7] considered the need for exergy analysis and thermodynamic optimization in aircraft development Marc A. Rosen [8] have done Sensitivity of exergy efficiencies of aerospace engines to reference environment selection, the results showed that The actual rational efficiency of the turbojet decreases with increasing altitude. The present papers evaluate a special modeling of Turbojet engine, analyzing it in term of energy, exergy of an aircraft turbojet engine. The Turbojet engine is a simple modification to the basic air-breathing gas turbine engine. A simplified cross-section of the turbojet engine is shown in Figure 1. The compressor and turbine are attached to a single shaft and separated by a combustor. Air is drawn into the engine at relatively high velocity due to the speed of the aircraft. The high velocity air enters the diffuser at state 1. The diffuser reduces the velocity in order to provide a pressure rise at state 2. The compressor increases the pressure and temperature of the air at state 3, which is mixed with fuel and burned in the combustor. The hot high pressure air leaving the combustor at state 4 is expanded through the turbine, which provides the power needed by the compressor. The pressure of the air leaving the turbine at state 5 is higher than atmospheric. In the Turbojet engine, the hot, high pressure air at state 5 enters a nozzle, which produces a high velocity flow of air leaving the turbojet at state 6 [9]. The J85-GE-21 turbojet engine is designed and manufactured by General Electric Company USA. It is a compact, high performance, lightweight turbojet engine comprising a nine-stage axial-flow compressor coupled directly to a two-stage turbine and an afterburner with a variable area exhaust nozzle [10]. The velocity of the air leaving the engine at state 7 is higher than the velocity of the air entering at state 1; therefore, a thrust force is produced [9]. In this paper, effects of design variables in turbojet engine, namely, the pressure ratio of Nozzle (RNozzle) and the after burner inlet temperature T5 on the exergetic performance of the turbojet engine are evaluated and discussed. In this way, a new computer code as developed in MATLAB_ programming language in this study. The study differs from the previous ones because of evaluating flight Mach number and analyzing the temperature effects of after burner on the exergetic cycle performance of the special turbojet engine. The thermal efficiency of the engine is defined as the ratio of the increase in the kinetic energy of the flow (which is analogous to the power provided by the engine) to the thermal energy delivered to the engine from combusting fuel:

- The flow is stable and constant.
- Air and combustion protects are considered to be ideal gas mixture.
- All components are assumed to be adiabatic.

ENERGY ANALYSIS

To find the optimum physical and thermal design parameters of the system, a simulation program was developed. Thus, temperature profile along the turbojet engine, input and output exergy, exergy efficiency, heat transfer surface area of each element were estimated to study the turbojet engine performance. The energy balance equations for various parts of the turbojet engine are:

Where CPg is considered to be a temperature variable to have a good agreement between simulation code and actual data for comparison purpose as follow:

Diffuser

$$V_1 = M_1\sqrt{\frac{C_{p1}R_1T_1}{C_{p1}-R_1}} \quad (1)$$

$$h(T_1) - h_1 - 1/2V_1^2 = 0 \quad (2)$$

The polytrophic efficiency can be expressed as a measure of entropy generation using Gibbs equation

$$\eta_{poly} = \left(1 - \frac{T_t ds}{dh_t}\right)^{\pm 1} \quad (3)$$

where the exponent is +1 for the compression and -1 for the expansion [6].

$$p_{t1} = p_1 \exp\left(\eta_{poly}{}^{\pm 1}\frac{S'(T_{t1}) - S'(T_1)}{R}\right) \quad (4)$$

The Compressor

$$T_B = T_A(1+(\frac{1}{\eta_{AC}})(r^{\frac{\gamma a-1}{\gamma a}} - 1)) \quad (5)$$

$$C_{pa} = 1.04841 - \left(\frac{3.8371T}{10^4}\right) + \left(\frac{9.4537T^2}{10^7}\right) - \left(\frac{5.49031T^3}{10^{10}}\right) + \left(\frac{7.9298T^4}{10^{14}}\right) \quad (6)$$

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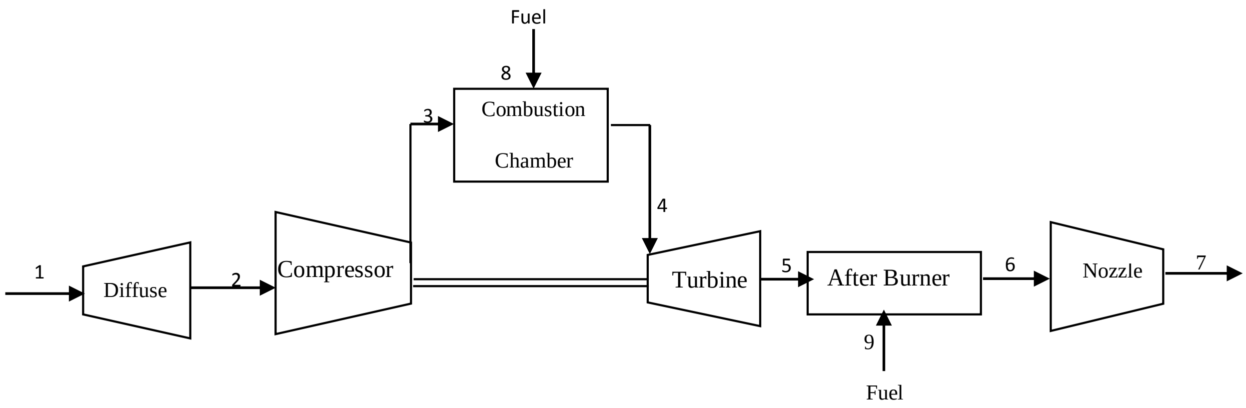

Figure 1. Schematic of a Turbojet engine Cycle

COMBUSTION CHAMBER (CC)

The combustion process is characterized by its initial and final temperatures, Tt3 and Tt4 and the fuel type, characterized by its composition $\vec{\beta}$, its temperature Tf, 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 $\overrightarrow{\alpha_4}$.

$$f_b = \frac{\overrightarrow{\alpha_0}\left(\vec{h}\left(T_{t4}\right)-\vec{h}\left(T_{t3}\right)\right)}{\vec{\beta}.\vec{h}\left(T_f\right)-\vec{\gamma}\vec{h}\left(T_{t4}\right)} \qquad (7)$$

$$\overrightarrow{\alpha_4} = \frac{\overrightarrow{\alpha_0} + f\vec{\gamma}}{1+f} \qquad (8)$$

Any loss in the combustor is characterized by a total pressure ratio of burner π_b [6].

$$p_{t5} = \pi_b p_{t4} \qquad (9)$$

$$\dot{m}_g = \dot{m}_a + \dot{m}_f \qquad (10)$$

$$C_{Pg}(T) = 0.991615 + \left(\frac{6.99703T}{10^5}\right) + \left(\frac{2.7129T^2}{10^7}\right) - \left(\frac{1.22442T^3}{10^{10}}\right) \qquad (11)$$

GAS TURBINE

$$\dot{W}_{AC} = \dot{W}_{GT} \qquad (12)$$

$$R_{GT} = \left(1-\frac{1}{\eta_{GT}}\left(1-\frac{T_{g6}}{T_{g5}}\right)\right)^{\frac{\gamma_g}{1-\gamma_g}} \qquad (13)$$

[9].

AFTER BURNER

the combustion Eq. (7) are used, with the difference that, the molar values of air are replaced with the molar values of gases exiting the gas turbine that are found from right hand side of Eq.(7)

NOZZLE

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 P0.

$$T_{t8} = T_{t7} \qquad (14)$$

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$$p_8 = p_0 \quad (15)$$

$$\left(\frac{S'(T_{t0}) - S'(T_0)}{R}\right) - \ln\left(\frac{p_{t8}}{p_8}\right) = 0 \quad (16)$$

$$V_8 = \sqrt{2\left(h_{t8} - h(T_8)\right)} \quad (17)$$

$$M_8 = V_8\sqrt{\frac{C_p(T_8)RT_8}{C_p(T_8) - R}} \quad (18)$$

If M_8 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.

$$M_8 = 1 \quad (19)$$

$$h_{t8} - h(T_{t8}) - \frac{M_8{}^2 C_p(T_{t8})RT_{t8}}{2\left(C_p(T_{t8}) - R\right)} = 0 \quad (20)$$

$$V_8 = \sqrt{2\left(h_{t8} - h(T_8)\right)} \quad (21)$$

$$p_8 = p_{t8}\exp\left(\frac{S'(T_{t0}) - S'(T_0)}{R}\right) \quad (22)$$

$$\rho_8 = \frac{P_8}{RT_8} \quad (23)$$

The thermal efficiency of the engine is the rate that kinetic energy is added to flow divided by the rate of fuel energy use: [6]

$$\eta_{th} = \frac{\dot{m}_0 \Delta KE}{\dot{m}_f LHV} \quad (24)$$

For the turbojet engine, thrust force is another performance metric considered.

$$F = \dot{m}_1[\,(1 + f_b + f_a)V_8 - (1 + f_b)V_1\,] + \frac{P_8 - P_1}{\rho_8 V_8} \quad (25)$$

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

$$SFC = \frac{\dot{m}_f}{F} \quad (26)$$

EXERGY ANALYSIS

Here, exergy can be divided into four distinct components. The three important ones are the physical exergy, kinetic exergy and chemical exergy. In this study, the one other component which is potential exergy are assumed to be negligible as the elevation [11, 12]. The physical exergy is defined as the maximum theoretical useful work obtained as a system interacts with an equilibrium state [13]. The chemical exergy is associated with the departure of the chemical composition of a system from its chemical equilibrium. The chemical exergy is an important part of exergy in combustion process. Applying the first and the second laws of thermodynamics, the following exergy balance is obtained:

$$\dot{E}x_Q + \sum_i \dot{m}_i ex_i = \sum_e \dot{m}_e ex_e + \dot{E}x_W + \dot{E}x_D \quad (27)$$

Where subscripts e and i are the specific exergy of control volume inlet and outlet flow, respectively and ED, is the exergy destruction. Other terms in this equation are as follows [14]:

$$\dot{E}x_Q = \left(1 - \frac{T_\circ}{T_i}\right)\dot{Q}_i \quad (28)$$

$$\dot{E}x_W = \dot{W} \quad (29)$$

$$\dot{E}x_K = \frac{1}{2}mV^2 \quad (30)$$

$$ex_{ph} = (h - h_\circ) - T_\circ(s - s_\circ) \quad (31)$$

$\dot{E}x_Q$ and $\dot{E}x_W$ are the corresponding exergy of heat transfer and work which cross the boundaries of the control volume, T is the absolute temperature (K) and ($\circ$) refer to the ambient conditions respectively.

From the system's exergy balance, the exergy destruction in HRSG is computed from:

$$\mathrm{Ex_D} = \dot{\mathrm{E}}\mathrm{x_i} - \dot{\mathrm{E}}\mathrm{x_e} \quad (32)$$

$$\dot{\mathrm{E}}\mathrm{x_{CH}} = \dot{m}\mathrm{ex_{mix}^{CH}}$$

The mixture chemical exergy is defined as follows:

$$ex_{mix}^{ch} = \left[\sum_{i=1}^{n} X_i ex^{ch_i} + RT_0 \sum_{i=1}^{n} X_i lnX_i + G^E\right] \quad (33)$$

The last term, GE; which is the excess free Gibbs energy is negligible at low pressure at a gas mixture. One can generalize the chemical exergy concept of fuel to every CaHbNgOd component [15]. The molar chemical exergy exch c of such a component will be

$$ex_c^{ch} = \left(\mu_{c,0} - \mu_c^e\right) \quad (34)$$

Where μ_c^e refers to the chemical potential of the component at the restricted dead state:

$$\mu_c^e = \alpha\mu_{\mathrm{co_2}}^{-\mathrm{e}} + \left(\frac{\beta}{2}\right)\mu_{\mathrm{H_2o}}^{-\mathrm{e}} + \left(\frac{\gamma}{2}\right)\mu_{\mathrm{N_2}}^{-\mathrm{e}} + (-\alpha - \frac{\beta}{4} + \frac{\delta}{2})\mu_{\mathrm{o_2}}^{-\mathrm{e}} \quad (35)$$

Where $\mu_{c,0}$ represents the chemical potential of the components at their thermo-mechanical equilibrium state with the standard ambient. For the evaluation of the fuel exergy, the above equation cannot be used. Thus, the corresponding ratio of simplified exergy is defined as the following:

$$\xi = \frac{ex_F^{ch}}{LHV_f} \quad (36)$$

The specific chemical exergies of liquid fuels on a unit mass basis can be determined as follows

$$\frac{e_{Ch}}{LHV} = \gamma_f = 1.0401 + 0.1728\frac{H}{C} + 0.0432\frac{O}{C} + 0.2169\frac{S}{C}\left(1 - 2.0628\frac{H}{C}\right) \quad (37)$$

RESULTS AND DISCUSSION

Turbojet engines are of the great importance nowadays due to their higher efficiency. The results show that after burner in the Turbojet engine cycle has the largest exergy destruction compared to other components. The reason is due to the large temperature difference between the flame temperature and working fluids which leads to produce more entropy and irreversibility (Figure 2).

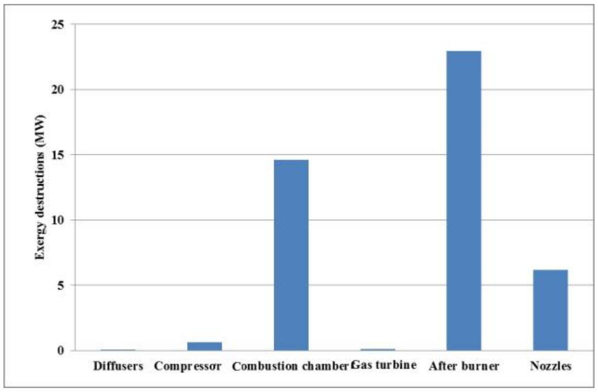

Figure 2. The irreversibility of the different components shown exergy destruction for specified Mach number (0.4)

To have a better insight into the analyses, a parametric study is performed with changes in exergy efficiency and exergy destruction. The results from the parametric study show that nozzle pressure ratio, after burner inlet temperature, are the most significant parameters in this Turbojet engine.

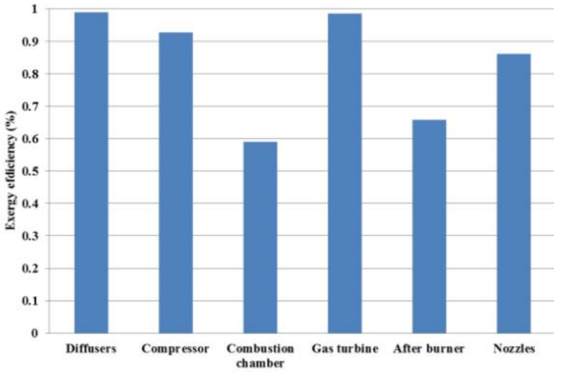

Figure 3. The irreversibility of the different components shown exergy efficiency for specified Mach number (0.4)

Figurs(4) to (5) show the parametric study of the changes in some important parameters of the cycle on propulsion efficiency of different Mach number. Figure (4) shows that by increase in the after burner

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temperature the on propulsion efficiency of the cycle increases for both. It shows that low Mach number is not suitable for turbojet engine. Also Figure (5) shows that for all nozzle pressure ratio the SFC of the cycle increase by increase in the Mach number of the turbojet engine. This is due to the fact that when the volume of air is increased the specific fuel consumption increases.

In addition, Figure (6) shows that by increase in the after burner temperature and Mach number, exergy efficiency of the after burner increases for both.

CONCLUSION

Performances of a special turbojet engine designing with some parameters (i.e. nozzle pressure ratio and after burner inlet temperature) were evaluated using exergy study approach based on combination of exergy analysis. Using parameters such as exergy and energy efficiency of the engine and its components, thrust were compared at several design points. Flight Mach number significantly affects the energetic efficiency of the engine. Owing to the rise of nozzle pressure ratio the exergetic and energetic efficiencies of the engine increase. Another result of response showed that after burner has the largest exergy destruction compared to other components. Also increase in the after burner temperature the on propulsion efficiency of the cycle increases for both.

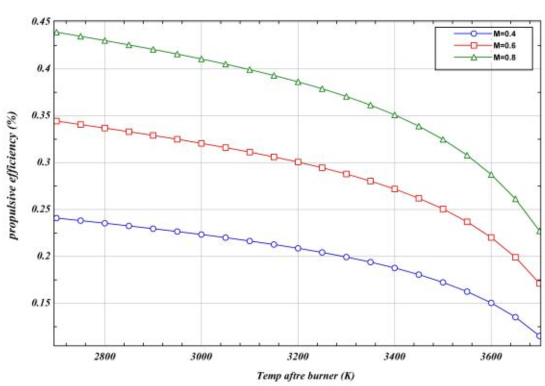

Figure 4. Propulsion efficiency change with Mach number difference for some nozzle pressure ratio

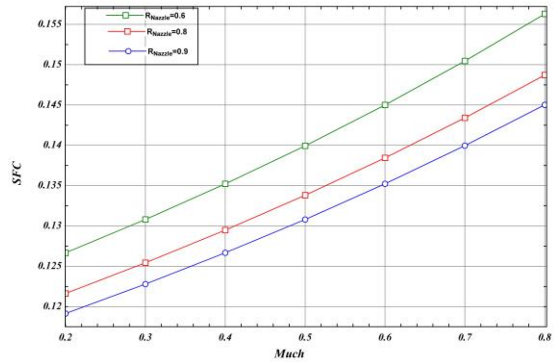

Figure 5. SFC change with Mach number Difference for some nozzle pressure ratio

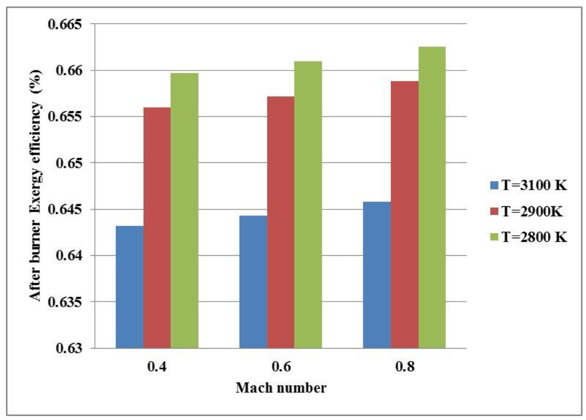

Figure 6. Exergy efficiency in after burner, change with Mach number difference for some after burner inlet temperature

NOMENCLATURE

C_p	specific heat ratio (KJ/kg)
ex	specific exergy (KJ/kg)
f	fuel exergy factor; fuel-air ratio
F	Thrust (Newton)
h	specific enthalpy (KJ/kg)
I	inlet
i	component
LHV	Lower heating value (kJ/kg)
KE	kinetic energy (KJ/kg)
m	mass flow rate (kg/s)
M	Mach number
R	ideal gas constant

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SFC	specific fuel consumption (Kg/N.S)
T	Temperature (K)
s	Entropy
V	Velocity (m/s)
W	work(KJ/s)
x	fraction of combustion equation species

Greek symbols

α	mass fraction
β	composition
γ	ratio of specific heats
η	efficiency
π	pressure ratio
ρ	density
χ	fuel depletion ratio

Subscripts and Superscripts

AC	Air Compressor
b	burner
ch	chemical
GT	Gas Turbine
o	Reference ambient condition

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