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Modeling the Thrust and Specific Fuel Consumption for a Hypothetical Turbojet Engine

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ABSTRACT
The turbojet is the first kind of jet engine to produce the thrust. The air enters to the engine and comes to the combustion chamber and after mixing with fuel and combustion, it is released as a hot gas out of the nozzle. Turbojet engines are widely used in various industries, especially in military industries. Because of the importance of fuel consumption amount and its impact on the turbojet engine thrust in this article, the thrust force and specific fuel consumption for a hypothetical turbojet engine in ideal state according to flight speed and total pressure ratio has been analyzed. In order to analysis, EES software, which was used as a robust programming application in the field of heat and fluids sciences, has been gaining attention of the credible scientific communities in recent years. Finally, the obtained results have discussed and analyzed. The results of this paper can help in finding optimum engine operation conditions that give us the most thrust power from consumed fuel

Keywords*: Turbojet engine, thrust force, specific fuel consumption, total pressure ratio, flight speed*

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INTRODUCTION

Since the air transportation has a major contribution in the countries' economy development, so the administration strategies to reduce fuel consumption of aviation sector which according to the latest data of large airlines, about 20–25% of their obtained income are allocated for the sale of airline tickets and this figure in a year reaches to more than 39 billion dollars, have the considerable importance. Therefore, the aircraft systems designers in various fields such as structural design, aerodynamic design of aircraft, etc. have made efforts in the last decades for reducing fuel consumption. With regard to the importance of the aircraft engine as thrust generation system, engine design subject is as the most sensitive of the design process and this topic has caused that the aircraft engine designers are constantly improving the aircraft thrust system. Turbine engines in various industries are very important, so that during the past decade in some countries have been conducted great efforts to design and construct of air and land turbine engines and this issue reflects the high will and tendency in the countries' military industries to achieve native turbine engine. Simulation and modeling of gas turbine engines are considered as one of the most complex dynamical systems available, always as an attractive issues in order to improvement the performance and control techniques, has been considered [1–3]. In order to analyze the performance of turbine engines in the design phase based on the aero thermodynamic behavior of engine and its components, the engine mathematical model is provided and using it, the engine performance is simulated and evaluated [4]. In the performance study of an engine having the performance characteristics in reference mode, which is one of the essential requirements must be extracted about each engine. In studying the performance of an engine by changing main parameters such as flight speed and total pressure ratio, engine functional parameters are calculated and functional characteristics such as thrust and specific fuel consumption and other parameters are obtained in the new conditions.

RESEARCH BACKGROUND

According to the importance of fuel consumption in aircraft, which was mentioned in the previous section, so many researches have been performed about it showing optimum use of fuel. In year 1973, Mr. Merrill and his colleagues could implement a general model about the turbofan engines thrust [5]. In 1997, Lu et al. have examined the aircraft control, through changes in aircraft thrust forces [6]. Goodman et al. have conducted an analysis on the turbine jet engine performance through changes in the input parameters of a turbine engine [7]. In 2000, Eikaza et al. have provided a design for the performance development and sustainability of aircraft engines [8]. In 2000, Esboda have provided the large database of known turbofan engines with bypass ratio above 2. The fundamental parameters such as weight, length and diameter of the fan, engine length, thrust force in horizontal state and mass flow of entrance air, bypass ratio, the fuel consumption for aircraft lifting are investigated all based on the aircraft engine thrust [9]. In 2008, Mr. Bethel has presented a simple design for fuel consumption performance and two-shaft turbofan engine thrust [10]. In 2008, Yonosof et al. offered a design to control aircraft engine thrust by using of flight information aircraft engines of diagnostic devices [11]. Moreover, among those who have many records in the field of turbine engine performance simulation, Karzak research work results has been published at various journals. Karzak also developed a software with name of "GASTURB" as turbine engines [12]. Francisco et al. had provided a turboshaft engine of 1000 kW for non-linear dynamic modeling and utilized this model to control the turboshaft engine system [13]. They also developed this engine in start condition, cruise control until snuff state. In Iran, the valuable papers in the field of turbojet engines have been offered. Homaei far and his colleagues have presented a method for improving the turbofan engines performance using a general algorithm method [14]. In 2008, Montazerin et al. proposed a method for improving the jet engines fuel system [15]

ANALYSIS

In this section, using the thermodynamic relations [16], we have paid for the analysis of different parts of turbojet engine and then by applying these relationships, we have analyzed the thrust force and specific fuel consumption for a hypothetical turbojet engine in an ideal state in terms of flight speed and calculated the total pressure ratio by using of Engineering Equation Solver (EES) software [17].

A-1 Increasing the pressure and speed decrease in air inlet in isentropic conditions.

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1-2 Isentropic density in compressors.
2-3 Heating during constant pressure.
3-4 Isentropic expansion in the turbine.
4-5 Accelerating warm fluid during re-expansion in the nozzle and creating thrust force in isentropic conditions.

Analysis of Air Inlet
In an air inlet, the total temperature was fixed and by having flight speed and air static temperature, the total temperature is calculated according to Equation (1),

$$T_{01} = T_{0a} = T_a + \frac{V_a^2}{2 * Cp_a} \quad (1)$$

In the real air inlet, we have always faced total pressure reduction, i.e.:

$$\begin{aligned} id &\rightarrow P_{01} = P_{0a} \\ act &\rightarrow P_{01} \neq P_{0a} \end{aligned} \quad (2)$$

$$\eta_r = \frac{P_{01} - P_a}{P_{0a} - P_a} \quad (3)$$

$$\eta_i = \frac{T_{01s} - T_a}{T_{01} - T_a} \quad (4)$$

$$M_a = \frac{V_a}{(K * R * T_a)^{0.5}}$$

By using the efficiency of the air inlet (2) and also isentropic efficiency of the air inlet (3) and flight Mach (4), we will have:

$$\frac{P_{01}}{P_a} = [1 + \eta_i * \frac{k_a + 1}{2} * M_a^2]^{\frac{k_a}{k_a - 1}} \quad (5)$$

Analysis of Compressor
By using the compressor efficiency (6) and compressor pressure ratio (7), compressor work is calculated:

$$\eta_c = \frac{T_{02s} - T_{01}}{T_{02} - T_{01}} \quad (6)$$

$$r_c = \frac{P_{02}}{P_{01}}, \frac{P_{02}}{P_{01}} = (\frac{T_{02s}}{T_{01}})^{\frac{K}{K-1}} \quad (7)$$

$$W_c^{\cdot} = m_a^{\cdot} \times Cp_a \times (T_{02} - T_{01}) \quad (8)$$

The relationship between compressor and turbine work using mechanical efficiency is defined as follows:

$$W_t^{\cdot} = \frac{W_c^{\cdot}}{\eta_m} \quad (9)$$

Analysis of Combustion Chamber
Due to the fact, that in the actual case in the combustion chamber there is a pressure drop, the relation (10) will be in the combustion chamber.

$$P_{03} = P_{02} - \Delta P \quad (10)$$

On the other hand, the ratio of air to fuel can be calculated from Equation (11)

$$f = \frac{\frac{Cp_g \times T_{03}}{Cp_a \times T_{02}} - 1}{\frac{LHV}{Cp_a \times T_{02}} - \frac{Cp_g \times T_{03}}{Cp_a \times T_{02}}} \quad (11)$$

Equation (12) also shows the efficiency of the combustion chamber

$$\eta_{cc} = \frac{(m_a^{\cdot} + m_f^{\cdot}) \times Cp_g - (m_a^{\cdot} \times Cp_a \times T_{02})}{m_f^{\cdot} \times LHV} \quad (12)$$

Analysis of Turbine
Using the turbine efficiency, as well as the mechanical efficiency and turbine pressure ratio, it is possible to analyze turbine according to (13–15).

$$\eta_t = \frac{T_{03} - T_{04}}{T_{03} - T_{04s}} \quad (13)$$

$$W_t^{\cdot} = \frac{W_c^{\cdot}}{\eta_m} \quad (14)$$

$$\frac{P_{04}}{P_{03}} = \left(\frac{T_{04s}}{T_{03}}\right)^{\frac{K}{K-1}} \qquad (15)$$

Analysis of Nozzle

Mode 1: The nozzle is not choked. In this case, the nozzle type is convergent and the relation (16) is established.

$$\frac{P_a}{P_{04}} \succ \frac{P^*}{P_{04}} \rightarrow P_a = P_5 \qquad (16)$$

Mode 2: The nozzle is choked. In this case, the type of nozzle is convergent, and equation (17) is established.

$$\frac{P_a}{P_{04}} = \frac{P^*}{P_{04}} \rightarrow P_5 = P^*, T_5 = T^*, M_5 = 1 \qquad (17)$$

Mode 3: The nozzle is choked. In this case, the nozzle type is convergent-divergent, and relation (18) is established

$$\frac{P_a}{P_{04}} \prec \frac{P^*}{P_{04}} \rightarrow P_5 \neq P_a, M_5 = 1 \qquad (18)$$

Analysis of Mode 1: With the efficiency of the nozzle according to (19) and calculating the velocity of the outlet gas from the nozzle, according to equation (21), the value of the thrust is obtained from equation (20)

$$\eta_j = \frac{T_{04} - T_5}{T_{04} - T_{5s}} \qquad (19)$$

$$\frac{P_{04}}{P_5} = \left(\frac{T_{04}}{T_{5s}}\right)^{\frac{K}{K-1}} \qquad (20)$$

$$V_5^2 = 2 \times Cp \times (T_{05} - T_5) \qquad (21)$$

$$F_s = m^{\cdot} \times (V_5 - V_a) \qquad (22)$$

Analysis of Modes 2 and 3: In this case, the trust will be calculated according to Equation (25).

$$T_5 = T^* = \frac{2}{k+1} \times T_{04} \qquad (23)$$

$$V_5^2 = K \times R \times T_5 \qquad (24)$$

$$F_s = m^{\cdot} \times (V_5 - V_a) + A_5 \times (P_5 - P_a) \qquad (25)$$

The specific fuel consumption is calculated in all three cases as follows:

$$SFC = \frac{f}{F_s} \qquad (26)$$

In the following, cycle is coded using ESS software for an assumed turbojet engine, the design specifications of which are given in Table (1).

Investigating the effects of changing the pressure ratio on the thrust (N) and fuel consumption (kg/N.S) on the fly M = 0:

As shown in Figure 1, with increasing pressure ratio to 12, the thrust will have a downward trend, this indicates that for this turbojet engine, the optimum thrust pressure ratio is 12. Meanwhile, the increase in the exhaust temperature from the combustion chamber causes an enthalpy to rise, which increases the rate of exhaust gases from the hot nozzle; as a result, it increases the thrust.

As shown in Figure 2, as the compressor pressure ratio increases, special fuel consumption decreases due to the fact that with increasing compressor pressure ratio thrust decreases; therefore, according to the SFC relationship, the specific fuel consumption should increase but considering that increasing the pressure ratio requires more fuel consumption; therefore, specific fuel consumption is reduced. Meanwhile, due to the fact that

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the increase in the temperature of the exhaust gases from the combustion chamber requires more fuel consumption. Therefore, with increasing the temperature of the exhaust gases from the combustion chamber, the specific fuel consumption also increases.

Investigating the effects of total pressure relation on thrust (N.S./kg) and specific fuel consumption in a specified non-zero Mach:

By comparing the diagrams in Figures 1 and 3, it is clear that at M = 0.85, the optimal pressure ratio is increased but the maximum thrust has been reduced. The cause of this can be attributed to various factors such as low air concentration at high altitudes and the occurrence of drag forces .On the other hand, as in Figure 1, the increase in the outlet temperature from the combustion chamber causes an enthalpy rise and this causes the speed of the exhaust hot gases from nozzle to increase and it increases the thrust.

As shown in Figure 4, in this case, as in Figure 2, with increasing compressor pressure ratio, the specific fuel consumption is decreasing .As in the previous state, it can be analyzed that the thrust decreases with increasing compressor pressure; therefore, according to the SFC relationship, the specific fuel consumption should increase, but considering that increasing the pressure ratio requires more fuel use; therefore, specific fuel consumption is reduced. In this case, in addition to the previous state, the fuel consumption has been accompanied by a massive increase in fuel consumption, due to the factors such as the reduction of air concentration and drag force, more fuel is needed to create thrust.

In this case, as in the previous state, attention should be paid to the fact that the increase in the temperature of the exhaust gases from the combustion chamber requires more fuel consumption; therefore, on increasing the temperature of the exhaust gases from the combustion chamber, the specific fuel consumption also increases.

Thrust changes (N) and specific fuel consumption (Kg/N.S) in general:

Figure 5 shows the relationship between the ratio of pressure, thrust and specific fuel consumption. According to Figure 5, we can obtain the optimal state of pressure ratio for thrust and fuel consumption.

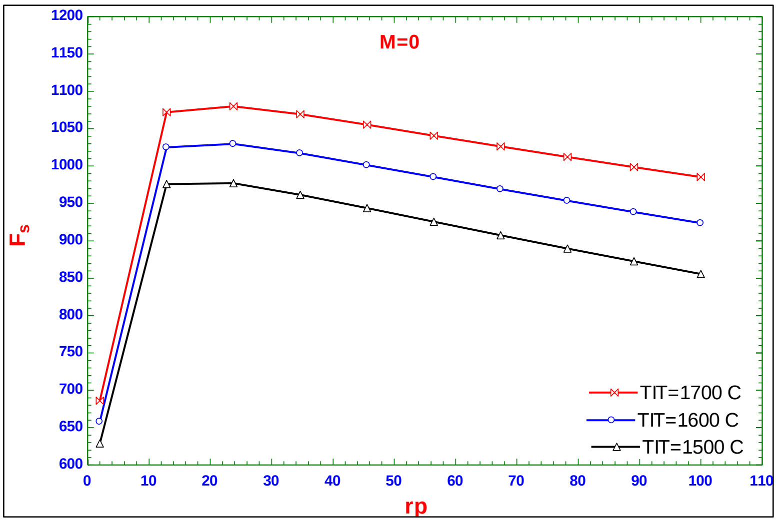

Fig. 1. *Trust Changes (N) in terms of the Pressure Ratio in Fly Mach M = 0.*

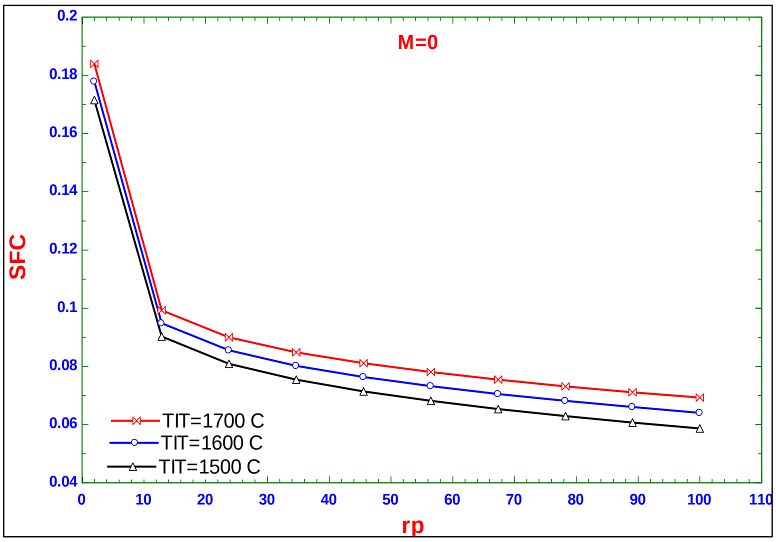

Fig. 2. *Specific fuel consumption changes (kg/N.S.) according to the pressure ratio at Mach M = 0.*

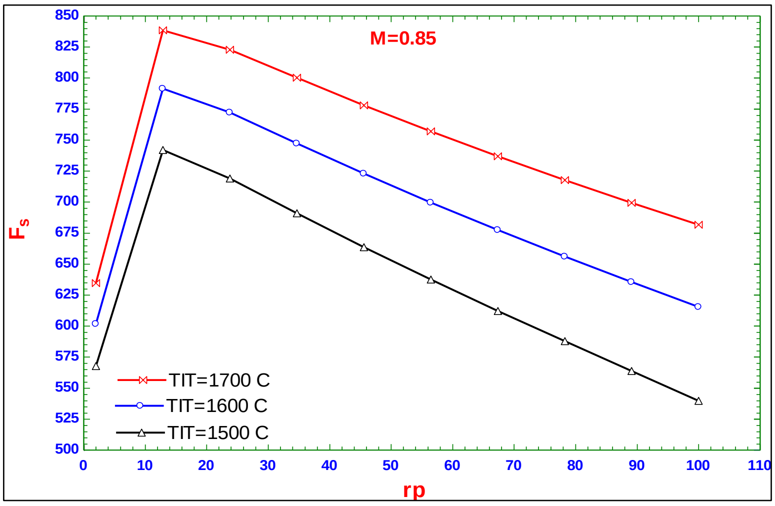

Fig. 3. *Thrust changes (N) in terms of the pressure ratio in fly Mach M = 0.85.*

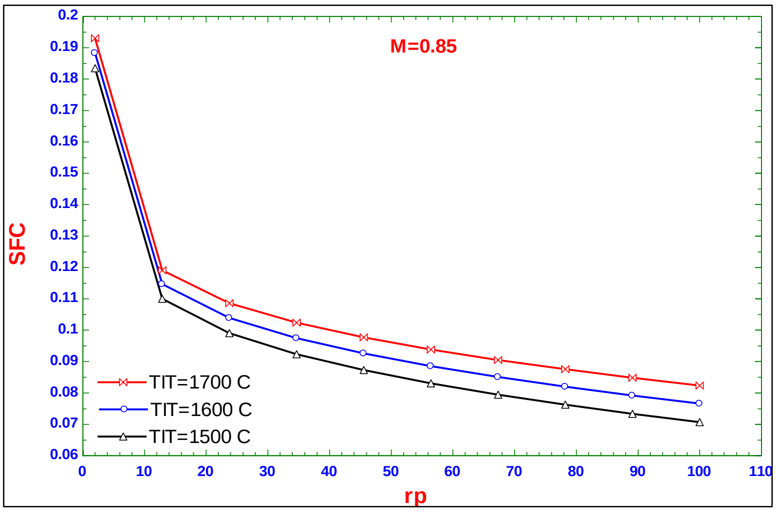

Fig. 4: *Specific Fuel Consumption Variations (kg/N.S.) in terms of Overall Pressure Ratio at Mach M = 0.85.*

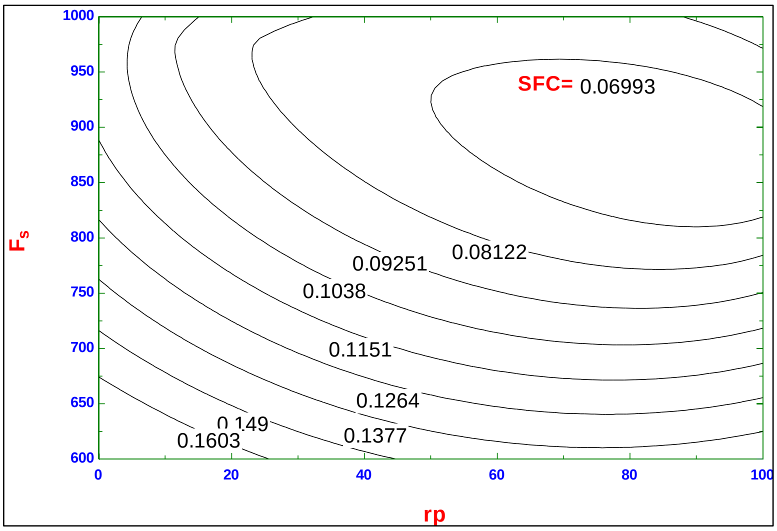

Fig. 5. *Thrust changes (N) and specific fuel consumption (kg/N.S.) in general.*

Table 1: *The desired Turbojet Engine Design Characteristics.*

C_{pa}	1.005kj/kg.k	η_i	0.93
K_a	1.4	H_a	m 5000
K	1.33	η_c	0.87
P	70 Kpa	η_t	0.9
R	18	η_{cc}	0.98
T_0	K 1300	η_m	0.98
P_c	0.04	η_j	0.95
LHV	Kj/kg 4300		

CONCLUSION

In this paper, we first studied the thermodynamic analysis of turbojet engines, and then the propulsion and specific fuel consumption was modeled for a hypothetical turbojet engine. In the first part of the analysis, at first, the thrust and fuel consumption were analyzed at M = 0, which indicated that with increasing the compressor pressure ratio of certain amount, thrust power is reduced. In this case, the increase in compressor pressure ratio is always associated with lower fuel consumption. In the second part, the analysis was performed at M = 0.85, the results of the analysis were repeated in the first part. However, due to the presence of factors such as lowering the air concentration and the entry of the drag force in the second case, in this case the maximum thrust is reduced and the maximum fuel consumption is increased. In both the cases, increasing the exhaust temperature from the combustion chamber will increase the thrust and fuel consumption.

According to the extracted diagrams, different combinations of different pressures and speeds and the temperature of the exhaust from the combustion chamber can be optimized by putting them together. The state where the thrusts are intended and at the same time other parameters, such as fuel consumption, are within range.

ABBREVIATION

V_a Flight speed **T_a Total temperature of free air** **C_{pg}Heat capacity at constant pressure for combustion products** **C_{pa}Heat capacity at constant pressure for air** **K_aAir specific heat ratio** **K_gSpecific heat ratio of combustion products** **P_aTotal pressure of free air** **r_pCompressor pressure ratio** **T_0 The outlet gases temperature from the combustion chamber** **P_{cc}Pressure decline of combustion chamber**	**LHV Fuel heating value** **η_iAir inlet Isentropic efficiency** **H_a Fly Height** **η_c Compressor efficiency** **η_t Turbine efficiency** **η_{cc}Combustion chamber efficiency** **η_mMechanical efficiency** **η_j Nozzle efficiency**

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