International Journal of I.C. Engines and Gas Turbines
Vol. 4: Issue 1
www.journalspub.com

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

*Gholamreza Zarepour[1], Kiumars Khani-Aminjan[2]**
[1]Department of Mechanical Engineering, Guilan University, Guilan, Iran
[2]Young Researchers and Elite Club, Islamic Azad University, Science and Research Branch, Tehran, Iran

ABSTRACT
Turbofan engine is a kind of jet engine in which a large part of the intake air without going into the combustion chamber that is exited from the terminal aperture. Turbofan engines have good efficiency in speed range of passenger aircraft and in terms of noise generation have also better functionality, for this reason in most of passenger aircraft this type of engine is used. Because of the importance of fuel consumption amount and its impact on the turbofan engine thrust, particularly in the commercial aircraft engine in this article the thrust force and specific fuel consumption for a hypothetical turbofan 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 and in recent years have been attention of the credible scientific communities. Finally, the obtained result has discussed and analyzed.

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

***Corresponding Author**
E-mail: kiomars.khani67@gmail.com

INTRODUCTION

The extent of the land, the distance range, the population centers scatter and natural irregularities and problems accessing land and sea transportation are among the factors that have caused the air transportation of passengers and goods in the world are known as one of the fastest, safest and most appropriate forms of transportation and taken into consideration.

In gradual trend towards of air travel compared to other modes of transportation, different factors affecting such as population growth, per capita income growth and preferential advantages the cost of air travel should not be ignored.

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 to 25 percent 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, has the considerable importance. Therefore, the aircraft systems designers in various fields such as 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 to improve 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 as one of the most complex dynamical systems available, always as an attractive industry issues in order to improve the performance and development of new 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 of it, the engine performance is simulated and evaluated [4]. structural design, aerodynamic design of aircraft and etc. have done many effort in the last decades for reduce fuel consumption. With regard to the importance of the aircraft engine.

In the performance study of per engine with having the performance characteristics in reference mode which is one of the essential requirements that 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.

Among turbine engines, the performance study and examine of turbofan engines which have due to many industrial and aviation applications, has particular importance. Today, most of modern passenger aircrafts are used the turbofan engines. In fact, the turbofan engines are a thing between turbojet and turboprop engines. In the turbofan engines, at first the air is compressed and then it enters into the combustion chamber and after the blast through nozzle or outlet nozzle is removed and during this process, it provides the necessary thrust force towards the aircraft to the forward, so that in the turbofan engines, the other amounts of air are passed also through bypass which finally it is attached to the hot exhaust gas and increases thrust force. With regard to the importance of turbofan engines, its analysis and modeling is necessary in order to achieve higher efficiency, therefore at first in this paper we dealt with the turbofan engine thermodynamic analysis and then by using of EES software, we have paid to study the impact of various parameters on the thrust force and specific fuel consumption. The analyzed turbofan engine in this paper is large compared to bypass ratio which its fan by the low-pressure turbine is rotated and is having two separate nozzles for fan flow and main flow.

Research Background

According to the importance of fuel consumption in aircraft which was mentioned in the previous section to it, so many researches have been performed about it and optimum use of fuel. In the year 1973, Mr. Merrill and his colleagues could implement a general model about the turbofan engines thrust [5]. In the year 1997, Lu et al., have examined the aircraft control, through changes for 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 the year 2000, Eikaza et al. have provided a design for the performance development and sustainability of aircraft engines [8].

In the year 2000, Esboda has provided the large database of known turbofan engines until the time for ratio of two number above. 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 the year 2008, Mr. Bethel has presented a simple design for fuel consumption performance and two-shaft turbofan engine thrust [10]. In the year 2008, Yonosof et al. have offered a design to control aircraft engine thrust by using of flight information aircraft engines of diagnostic devices [11-12].

Moreover, among those who have many recorded in the field of turbine engine performance simulation, can be implied to Karzak which his researches work results have been published from 1978 to 2010 at conferences to simulate the steady state performance and various journals. Karzak also has been developed a software with name of "GASTURB" as turbine engines.

Francisco et al. [13] had provided a turboshaft engine of 1000 kW for nonlinear dynamic modeling and were utilized this model to control of the turboshaft engine system. They also have developed this engine in start condition, cruise control until snuff state. In inside of Iran, as well as 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 the year 2008, Montazerin et al. have proposed a method for improving the jet engines fuel system [15]. Soltani has studied an analysis of the performance of a modern gas turbine in the functioning conditions at design point and off-design point using stage staking method [16]. Nazari [17] in Sharif University of technology, by using core gas generator on the existing turbojet engine in the gas turbine laboratory and designed turboshaft engines in it, was performed this static and dynamic engine modeling and has been extracted the required functions for turboshaft engine control. Figure 1

ANALYSIS

In this section using the thermodynamic relations [18], we have paid to analysis of the different parts of turbofan engine and then by applying of these relationship, we have analyzed the thrust force and specific fuel consumption for a hypothetical turbofan engine in ideal state in terms of flight speed and have calculated the total pressure ratio by using of EES software [19].

A-1-Increasing the pressure and speed decrease in air inlet in isentropic conditions.
1-2- Isentropic density in the fan;
2-3- Isentropic density in high-pressure compressors;
3-4- Heating during constant pressure;
4-5- Isentropic expansion in the high-pressure turbine;
5-6- Isentropic expansion in the low-pressure turbine;
6-7-Accelerating of warm fluid during re-expansion in the warm nozzle and creating thrust force in isentropic conditions.
8-1- Accelerating of cold fluid during re-expansion in the cold nozzle and creating thrust force in isentropic conditions.

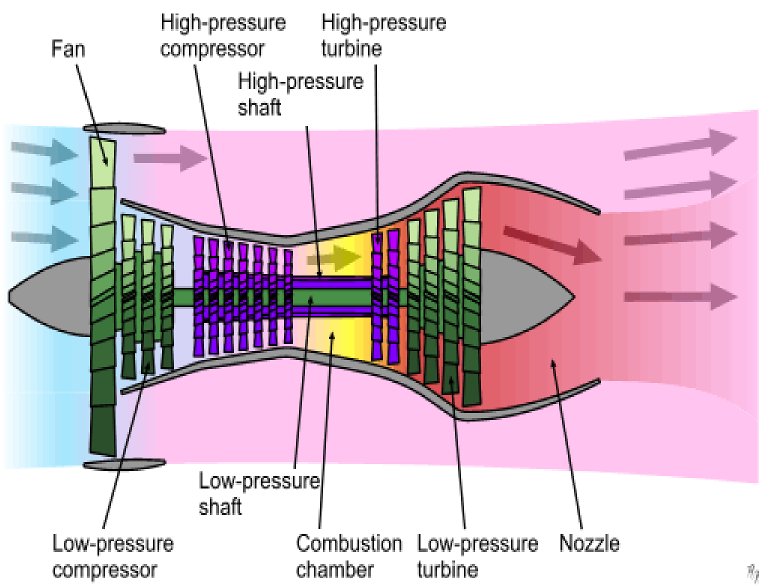

Fig. 1. *The general view of a turbofan engine [18].*

Analysis of Air Inlet

In the air inlet, the total temperature was fixed and by having of 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 are faced always with total pressure reduction, i.e.:

$$id \rightarrow P_{01} = P_{0a}$$
$$act \rightarrow P_{01} \neq P_{0a}$$

$$\eta_r = \frac{P_{01} - P_a}{P_{0a} - P_a} \quad (2)$$

$$\eta_i = \frac{T_{01s} - T_a}{T_{01} - T_a} \quad (3)$$

$$M_a = \frac{V_a}{(K * R * T_a)^{0.5}} \quad (4)$$

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:

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

Fan Analysis

$$f_{pr} = \frac{P_{02}}{P_{01}} \quad (6)$$

By having fan pressure ratio (6) and fan fη efficiency, we will have:

$$\frac{T_{02}}{T_{01}} = [1 + \frac{1}{\eta_f} * (f_{pr}^{\frac{k_a - 1}{k_a}} - 1)] \quad (7)$$

Cold Nozzle Analysis

Now, by using the cold nozzle efficiency and also P02 value of P * which is the bottleneck pressure, according to Equation (8) is calculated.

$$\frac{P^*}{P_{02}} = [1 - \frac{1}{\eta_{i,c}} * (\frac{k_a - 1}{k_a})]^{\frac{k_a}{k_a + 1}} \quad (8)$$

By assuming the lack of choking nozzle ($P_8 = P_a$), we will have:

$$T_{02} - T_8 = \eta_{i,c} * T_{02} * [1 - (\frac{P_a}{P_{02}})^{\frac{k_a - 1}{k_a}}] \quad (9)$$

$$T_{02} = T_{08} = T_8 + \frac{V_8^2}{2*Cp_a} \quad (10)$$

The outlet gas speed from cold nozzle, according to Equation (11) will be obtained.

$$V_{j,c} = (2 * Cp_a * (T_{08} - T_8))^{0.5} \quad (11)$$

High Pressure Compressor Analysis

Using the fan pressure ratio can be calculated compressor pressure ratio $P_{tot} = \frac{P_{03}}{P_{01}}$ according to Equation (12).

$$\frac{P_{03}}{P_{02}} = \frac{P_{03}}{P_{01}} * \frac{P_{01}}{P_{02}} \quad (12)$$

By having compressor efficiency (13) according to Equation (14), the total temperature at compressor outlet of high pressure will be obtained.

$$\eta_c = \frac{T_{03s} - T_{02}}{T_{03} - T_{02}} \quad (13)$$

$$T_{03} - T_{02} = \frac{T_{02}}{\eta_c} [(\frac{P_{03}}{P_{02}})^{\frac{k_a - 1}{k_a}} - 1] \quad (14)$$

$$P_{04} = P_{03} * (1 - \frac{\Delta P}{P_{03}}) \quad (15)$$

Combustion Chamber Analysis

By considering the pressure decline in the combustion chamber, the outlet gases pressure from the combustion chamber according to Equation (15) is calculated.

$$\dot{m}_h h_h + \dot{m}_f h_f = (\dot{m}_f + \dot{m}_h) h_p \quad (16)$$

From mass balance in the combustion chamber, we will have:

High Pressure Turbine Analysis

High pressure turbine was connected to the high-pressure compressor and according to mechanical efficiency, we will have:

$$W_{hpt} = \frac{W_{hpc}}{\eta_m} \quad (17)$$

$$\frac{P_{05}}{P_{04}} = [1 - \frac{1}{\eta_{hpt}} * (1 - \frac{T_{05}}{T_{04}})]^{\frac{k_g}{k_g - 1}} \quad (18)$$

Low Pressure Turbine

Low pressure turbine was connected to the fan and according to mechanical efficiency, we will have:

$$W_{lpt} = \frac{W_f}{\eta_m} \quad (19)$$

Hot Nozzle Analysis

In hot nozzle analysis, we have:

$$\frac{P^*}{P_{06}} = [1 - \frac{1}{\eta_{j,h}} * (\frac{k_g - 1}{k_g + 1})]^{\frac{k_g}{k_g - 1}} \quad (20)$$

By assuming the lack of choking nozzle ($P_7 = P_a$), the outlet gases speed from hot nozzle according to Equation (21) is calculated.

$$V_{j,h} = V_7 = (2 * Cp_g * (T_{06} - T_7)) \quad (21)$$

On the other hand, according to Equation (22), we will have:

$$T_{06} = T_{07} = T_7 + \frac{V_7^2}{2 * Cp_a} \quad (22)$$

Using the ratio of by-pass (23) and the air-fuel ratio according to Equation (24), specific thrust according to Equation (25) will be calculated.

$$B = \frac{\dot{m}_c}{\dot{m}_h} \quad (23)$$

$$f = \frac{\dot{m}_f}{\dot{m}_h} \quad (24)$$

$$Fs = \frac{F}{\dot{m}_h} = B * V_{i,c} + (1 + f) * V_{j,h} - (B + 1) * V_a \quad (25)$$

$$SFC = \frac{\dot{m}_f}{F} = \frac{f}{((1 + f) * V_{j,h} + B * V_{i,c} - (1 + B) * V_a)} \quad (26)$$

However, according to Equation (26), specific fuel consumption is achieved.

In the following, the above cycle with coding through EES software for an assumed turbofan engine which its design specifications have shown in Table 1 to be analyzed.

Table 1. *The desired turbofan engine design characteristics.*

270 m/s	V_a flight speed
225.8 K	T_a total temperature of free air
kJ/kg.k 1.147	Cp_g Heat capacity at constant pressure for combustion products
kJ/kg.k 1.005	Cp_a Heat capacity at constant pressure for air
1.4	K_a Air specific heat ratio
1.333	K_g Specific heat ratio of combustion products
8	f_rp Fan pressure ratio
12	rp_tot total pressure ratio
1200 K	T_4 The outlet gases temperature from the combustion chamber
0.04	By-pass ratio

0.08	P_cc Pressure decline of combustion chamber
4300 kJ/kg	LHV fuel heating value
0.93	η_r air inlet efficiency
0.84	η_i air inlet Isentropic efficiency
0.85	η_f fan efficiency
0.93	η_c compressor efficiency
0.93	η_hpt High pressure turbine efficiency
0.94	η_lpt Low pressure turbine efficiency
0.98	η_cc Combustion chamber efficiency
0.98	η_m mechanical efficiency
0.95	η_ic cold nozzle efficiency
0.94	η_ jh Hot nozzle efficiency

The study of impacts of the flight speed changes on the thrust (NS/kg) and specific fuel consumption (kg/NS) in a definite Mach:

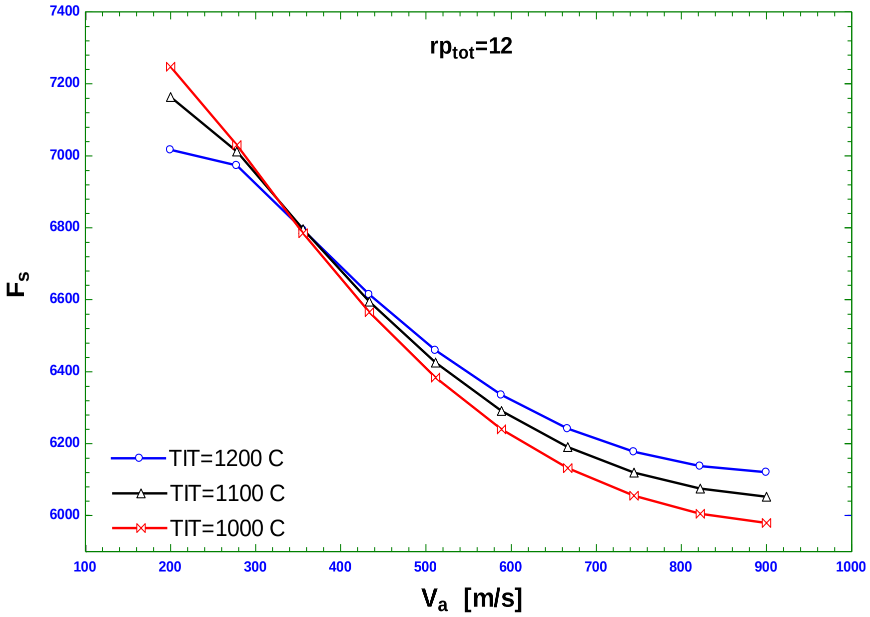

Fig. 2. *Thrust changes in terms of flight speed at a constant total pressure ratio.*

As it is determined from the Figure 2, by increasing the flight speed, the thrust force will be downward that Fs relation is also indicating of this issue. However, the outlet temperature increase of the combustion chamber causes to increase of enthalpy that this issue makes that the outlet gas speed from the hot nozzle is increased, thus it is increasing the thrust, but that is why at speeds less than 360 m / s, the outlet temperature increase of the combustion chamber causes to reduce of the thrust, can be analyzed that in this form the optimal use of fuel is not conducted, because as we know, the outlet temperature increase of the combustion chamber which leads to the thrust and flight speed increase, is required to the greater fuel consumption, now if we increase the fuel consumption, but the speed is low, in fact, we have not efficient use of fuel, therefore considering that the fuel consumption factor in the thrust is an important factor that in Fs relation is determined, the thrust will be reduced.

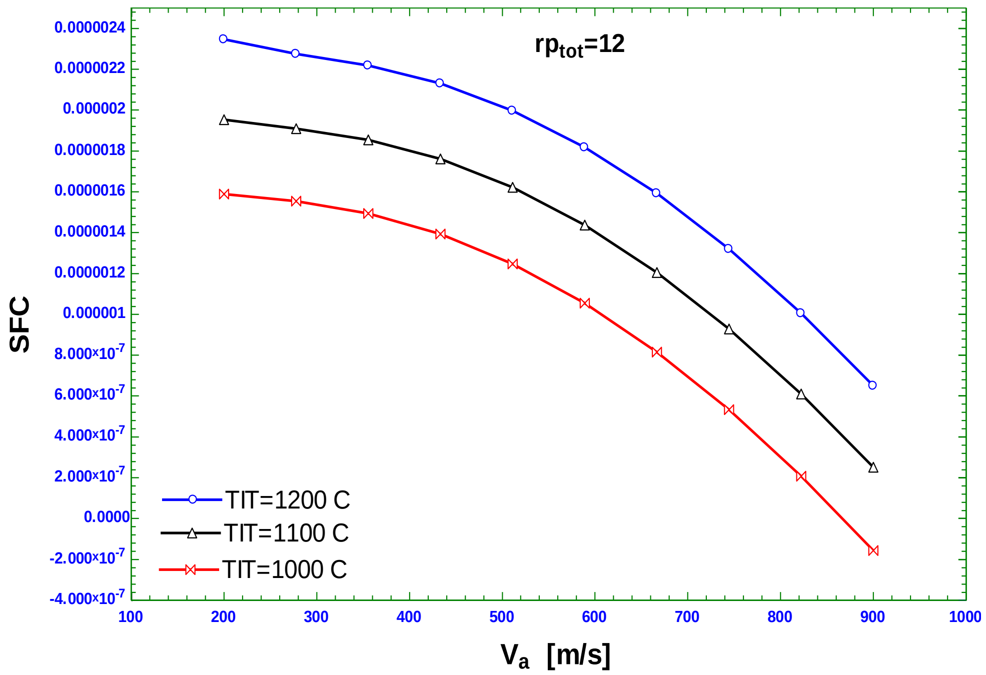

Fig. 3. *Specific fuel consumption changes in terms of flight speed at a constant total pressure ratio.*

As it is determined from the Figure 3, by increasing the flight speed, the specific fuel consumption is reduced, but this reduction compared to the thrust reduction, has less slope which its reason is that by increasing the flight speed, the thrust is reduced, therefore according to SFC relation, the specific fuel consumption should be increased, but due to the increase of the flight speed is required s greater use of fuel, so the specific fuel consumption is reduced, but this reduction compared to the thrust reduction, has also less slope.

The study of impacts of the total pressure ratio on the thrust (NS/kg) and specific fuel consumption (kg/NS) in a definite Mach:

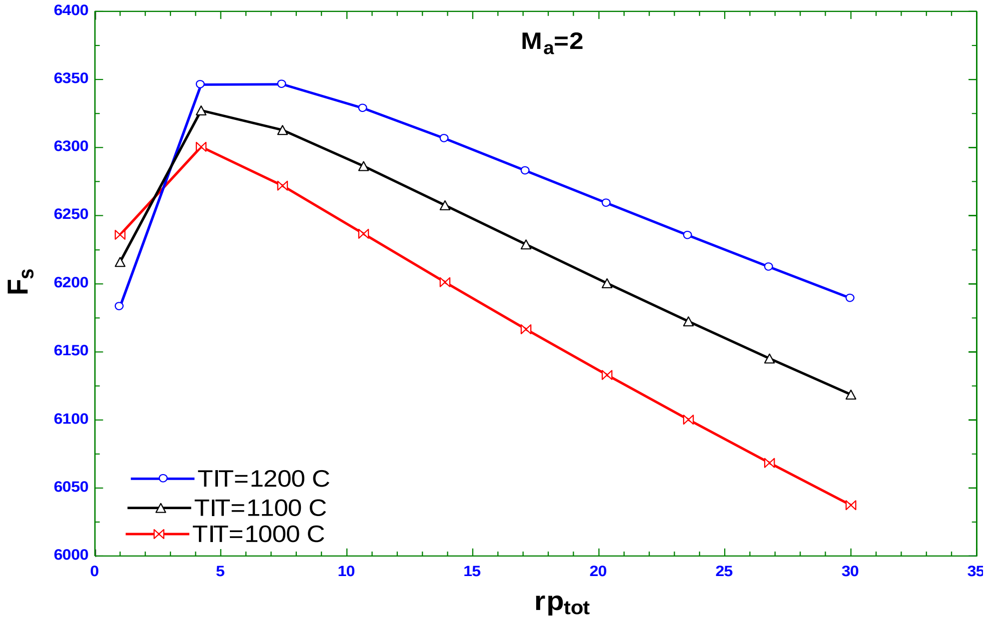

Fig. 4. *Thrust changes in terms of the total pressure ratio at a constant Mach.*

As it is determined from the Figure 4, the thrust amount maximum for the assumed turbofan engine is about 5 which indicates that for this engine in flight Mach of 2 is obtained the thrust amount maximum compared to the total pressure ratio equal to 5.

It should be noted that the total pressure ratio is the outcome of fan pressure ratio and compressor. In addition, due to the thrust increase with outlet temperature of turbine as like the previous modes, is as a result of the outlet gas enthalpy increase of the hot and cold nozzle.

But the reason of thrust reduction by increasing the outlet gases temperature from the combustion chamber at total temperature ratio less than 3, can be stated due to the lack of efficient use of fuel, it means that although we can create the total temperature ratio less than 3 with less fuel, but for doing this, it should be consumed more fuel and in fact we have consumed the fuel in the vain way.

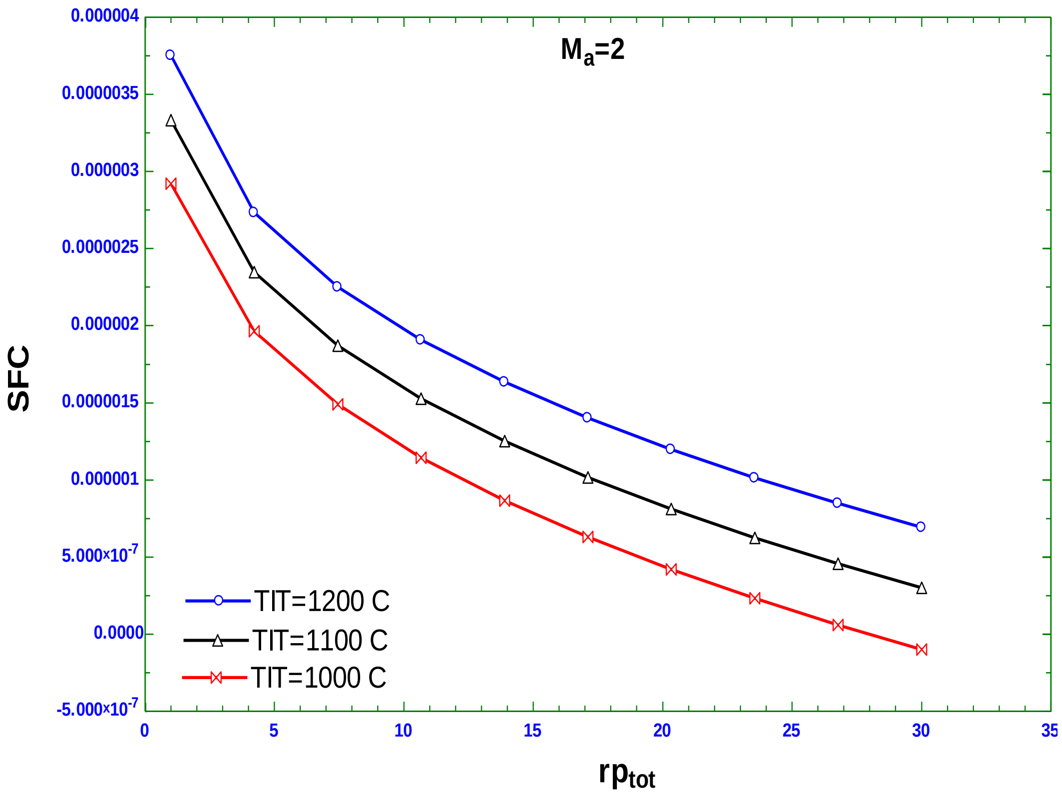

Fig. 5. *Specific fuel consumption changes in terms of the total pressure ratio at a constant Mach.*

As it is determined from the Figure 5, by increasing the total pressure ratio, specific fuel consumption is reduced which its reason is that, as it is stated in the analysis of Figure 4, normally the total pressure ratio increase leads to the thrust decrease, but the total pressure ratio increase is required more fuel consumption that the outcome of these two factors will be specific fuel consumption decrease.

In relation to specific fuel consumption increase with the exhaust gases temperature increase from the combustion chamber is very clear that to increase the temperature of the exhaust gases from the turbine should be consumed more fuel, so specific fuel consumption will increase.

The relationship between the ratio of the total pressure, thrust (NS/kg) and specific fuel consumption (kg/NS) in general state:

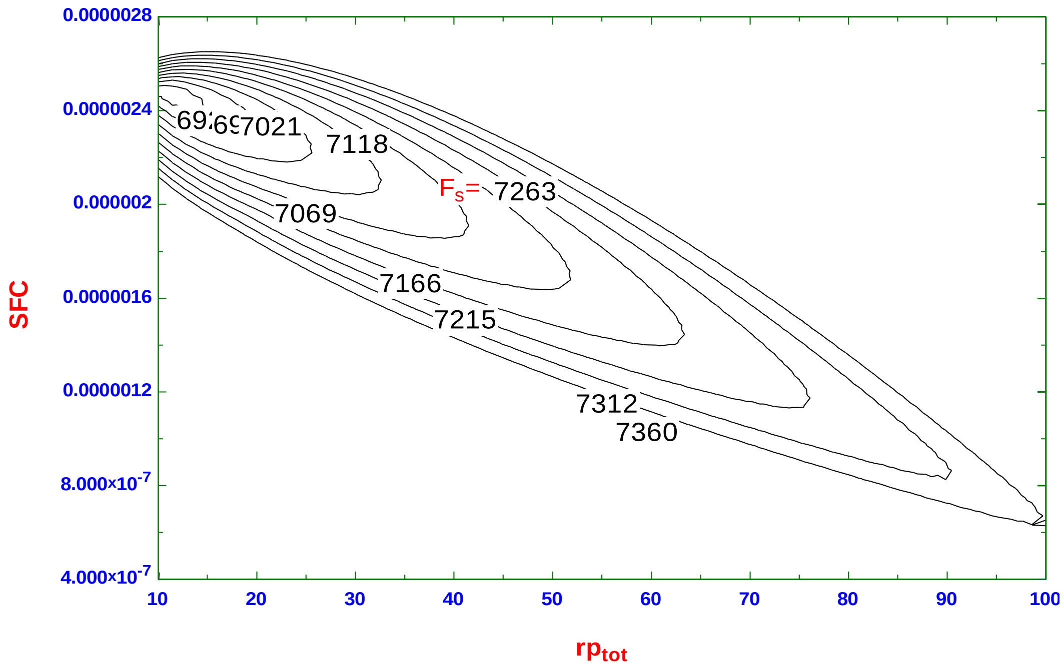

Fig. 6. *The relationship between the ratio of the total pressure, thrust and specific fuel consumption in general state.*

As it is determined from the Figure 6, it is observed that by increasing the thrust, specific fuel consumption is reduced. According to the Figure 6, simultaneously show the relationship between the total pressure ratio, the thrust and specific fuel consumption, therefore using this diagram can be found optimal state for the analyzed turbofan engine.

CONCLUSION

In this paper, at first we have paid to thermodynamic analysis of turbofan engine and then thrust force and specific fuel consumption for an assumed turbofan engine has been modeled. In the analysis first section, at first it was paid to investigate the impacts of flight speed change on the thrust and specific fuel consumption at a definite pressure ratio that an examination of the relevance diagrams was indicated that with the increase Va in a definite rp, the values of Fs and SFC always are reduced. However, the increase of TIT value in this state causes the increase of SFC, but for flight speed less than 360 m/s with the increase of TIT causes the increase of Fs, but in flight speed higher than 360 m/s with the increase of TIT, Fs value always are increased. In the 2nd section, an analysis based on the impacts of the total pressure ratio change was conducted on the thrust and specific fuel consumption at a definite Mach that the obtained results was indicated that at a definite Mach with the increase of rp value up to 5, Fs value is increased and for rp value higher than 5, Fs value is decreased, but with the increase of rp, SFC value is always reduced.

Moreover, TIT value increase in this case, also as like previous state always causes SFC increase, but TIT value increase for rp less than 3 causes Fs decrease and for rp value higher than 3 with TIT increase always Fs increases. According to the extracted charts in different flight speed and pressures ratio and outlet temperature of the different combustion chamber, by putting together them, can be found the optimal state. When the desired thrust is provided and at the same time, the other parameters such as fuel consumption is placed within the allowable range.

REFERENCES

[1] Y. Santosh. Performance analysis of J85 turbojet engine matching thrust with reduced inlet pressure to the compressor, *Master Thesis*. University of Toledo, 2010.

[2] K.G. Kyprianidis, A.I. Kalfas. Dynamic performance investigations of a turbojet engine using a crossapplication visual oriented platform, *Aeronaut J*. 2008; 2(4): 12–44p.

[3] K. Jayachandran. Modeling and simulation of single spool jet engine, *Master Thesis*. University of Cincinnati, 2003.

[4] O. Balli, H. Aras, A. Hepbaslı. Exergetic and exergoeconomic analysis of an aircraft jet engine (AJE), 2008; 5, 567–581p.

[5] G.L. Merril. Turbofan propultion for General Aviation, *SAE Int J*. 1973; 32(3): 23–65p.

[6] L.u. Ping, B. Johny. Controlling aircraft with engine thrust only: nonlinear challenges, *Int J Thermodyn Sci*. 1995; 350(2): 21–44p.

[7] G. Thiery, H. Simon, S. Pascal. Theoretical analysis of environmental and energetic performance of very high temperature, *Thermodyn Sci*. 1999; 380: 442–81p.

[8] I. Daniel, R. Christian. *Thurast Vectoring for Eurofighter*. 2000; 2, 89–91p.

[9] C. Sroboda. Turbofan engine database as a preliminary design tool, *Aircraft Des*. 2000; 3: 17–31p.

[10] M. Battel, T.M. Young. Simplified thrust and fuel consumption models for modern two shaft turbofan engines, *J Aircraft*. 2008; 45: 1484-148p.

[11] S. Yunusoy, Y. Labendik, E. Kopytor. Turbofan thrust control on flight information in aircraft engine diagnostic system, *J Aircraft*. 2008; 45: 1484–6p.

[12] K.J., 2004. Gas Turb 10 User Manual.

[13] F.B. Filho, L.C. Goes, A.V. Oliveira, R.W. Bosa, G.S. Fernandes. Dynamic modelling nonlinear and control system for a turboshft, In: *12th Pan-American Congress of Applied Mechanics*. America, January 21, 2010, 2–6p.

[14] A. Hamaifar. system optimization of turbofan engines using genetic algorithms, *Appl Math Model*. 1994; 16: 76–88p.

[15] M. Montazeri, A. Safri, S. Jafan. optimization of Jet engine fuel control system for safety considereation. Tev (th) Iranian Aerospace society conference. Sharif university of Thechnology, 2008.

[16] A. Bolonina, G. Bolonins, D. Blumberga. Analysis of the impact of decreasing district heating supply temperature on combined heat and power plant operation, 2014; 14(1): 41–6p.

[17] T. Baklacioglu, M. Cavcar. Aero-propulsive modelling for climb and descent trajectory prediction of transport aircraft using genetic algorithms, 2014; 118: 1–11p.

[18] S. Farokhi. *Aircraft Propulsion*. John Wiley & Sons; 2009.

[19] S.A. Klein. Engineering Equation Solver – Copyright 1992-2010.