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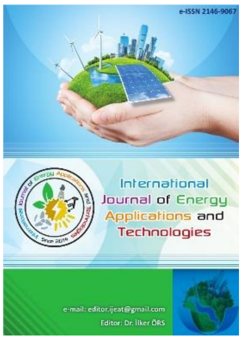

Original Research Article

Examination of parametric cycle analysis of a turbofan engine with Python code

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ABSTRACT

In this study, the performance analysis of the engine was carried out according to the parameters determined by parametric cycle analysis in turbofan engines with afterburner and separate exhaust streams. The main purpose of the study is to determine the relationship between engine performance values, design parameters and flight ambient values. For this, the effects of Mach number, compressor pressure ratio and bypass ratio values on specific thrust, fuel-air ratio, specific fuel consumption and engine efficiency were investigated. The open source code PYTHON programming language was used in the study and the results were presented as graphically. Results consistent with the studies in the literature were obtained. According to the results, it was observed that the specific thrust values and the total efficiency values increased with the increase of the Mach number. On the other hand, with the increase of the Mach number, the fuel-air ratio decreased and more fuel consumption was required to provide the required thrust value. In the case of afterburning, as the bypass ratio increases, the specific thrust value and the total efficiency value decrease, whereas the specific fuel consumption of turbofan engines without afterburning increases.

Keywords: Afterburner; Performance analysis; Thrust; Turbofan engine

1. Introduction

Nowadays, turbofan engines are used in modern aircraft. Turbofan engines have features that combine the high speed and altitude capability of turbojet engines with the efficiency and high response capability of the turboprop engine. In recent years, turbofan engines have become indispensable in the commercial field due to factors such as reducing the noise below the specified limit values and reducing fuel consumption [1].

A literature review was conducted and studies to evaluate engine performance and efficiency were examined. In these studies, performance curves were obtained according to the parameters examined by using parametric cycle analysis or engine performance analysis according to different engine types. Cycle analysis basically examines the thermodynamic change in the flow occurring in the engine and is divided into two as parametric cycle analysis and engine performance analysis.

Turan and Karakoç [2], conducted design point (on design) and off design analyzes of afterburner and without afterburner engine types in their study named gas turbine engines performance analysis and evaluation program. As a result of this study with the help of the created GAZTUSIM program, the time-independent design performance of seven different axial flow engine types used in airplanes can be calculated according to different flight and design conditions. Gokeniş and Kodal [3], analyzed the change specific fuel consumption, fuel-air ratio and specific thrust according to changing Mach number and compressor pressure ratio for turbojet engine. Patel [4], was carried out using the Numerical Propulsion System Simulation (NPSS) software.

The effect of the bypass ratio and the fan pressure ratio along with variation in Mach number were studied in his thesis. Optimum values of bypass ratio and fan pressure ratio were also obtained for each altitude selected for off-design performance.

Liew and et al. [5], examined on a parametric cycle analysis of a dual-spool, separate-flow turbofan engine with an Interstage Turbine Burner (ITB). The objective of their study was to use design parameters, such as flight Mach number, compressor pressure ratio, fan pressure ratio, fan bypass ratio, and high-pressure turbine inlet temperature to obtain engine performance parameters, such as specific thrust and thrust specific fuel consumption.

Dankanich and Peters [6], studied to introduce the trends of a turbine engine when compared across an increasing BPR. This analysis incorporated the principal equations governing the performance of a turbine engine and through a computer simulation, varied the bypass ratio to show how the specific fuel consumption decreases as bypass ratio increases. Shwin [7], investigated the performance analysis (off-design) of high bypass turbofan engines with separate flow and non-afterburning. Then thrust, specific fuel consumption, air mass flow rate, bypass ratio, corrected mass flow rate, fan and compressor pressure ratio of the engine were characterized in different altitudes and subsonic flight Mach numbers.

In another study, for MALE UAV propulsion presented parametric analysis of a low bypass turbofan engine. Analysis of micro turbofan engine was made using MATLAB and GSP 11 programs. According to results, the thrust developed by the engine and the Thrust Specific Fuel Consumption (TSFC) depend on the pressure ratio, the mass flow rate of air and Mach number in the analysis [8].

Some performance parameters of JT9D turbofan engine were analyzed by Onal and Turan [9]. The engine was a high bypass turbofan engine which powers a wide-body aircraft and it produces 206 kN thrust force. The parameters for the engine included the calculation of power, specific fuel consumption, and specific thrust, engine propulsive, thermal and overall efficiencies according to the various definitions given in the literature. Turan and et al. [10], carried out the performance analyzes (off design) of high bypass, split flow and afterburner turbofan engines used in civil passenger aircraft. The effects of flight Mach number on engine thrust, specific fuel consumption, air flow, bypass ratio, corrected air flow, fan and compressor pressure ratios were investigated for different altitudes and subsonic flights.

Ekici and et al. [11], defined the performance evaluation parameters for a turbojet engine used in airplanes. These were specific fuel consumption, thrust efficiency, thermal efficiency, total efficiency and exergy efficiency. These performance parameters had been calculated for a sample turbojet engine.

A mathematical model for calculation of single-spool turbojet engine off-design performance was developed by ref [12]. Calculation results for a range of flight parameters and various throttle settings were presented for the known turbojet engine. A new type of turbofan which detonates a fuel-air mixture was theoretically found to perform better than a conventional turbofan [13]. A parametric analysis of the new detonation-type turbofan was developed and used to calculate the performance parameters.

Turan and Karakoç [14], investigated effects of the fan pressure ratio and the bypass ratio on engine overall efficiency for afterburning and separate flow turbofans in another work. With this purpose, fan pressure ratio, bypass ratio, overall efficiency three dimensional graphs were developed and then computer experiment results were evaluated for three different flights Mach number.

Parker and Guo [15], presented the development of a generic component level model of a turbofan engine simulation with a digital controller, in an advanced graphical simulation environment. The goal of this effort was to develop and demonstrate a flexible simulation platform for future research in propulsion system control and diagnostic technology. A previously validated FORTRAN based model of a modern, high-performance, military-type turbofan engine was being used to validate the platform development. Turbofan engine performance graphs including thrust, thrust specific fuel consumption and thermal, propulsive and the overall efficiencies were investigated by Gorji and et al. [16]. Moreover, the graphs of turbofan components such as the high pressure and low pressure compressor pressure ratio, exit temperature pressure from high pressure compressor, combustor inlet temperature, corrected inlet mass flow rate of compressor and fan and bypass ratio were evaluated.

Roux [17], presented a parametric cycle analysis for the ideal scramjet. This permits the description of the ideal scramjet via simple algebraic equations similar to that for the ideal ramjet, ideal turbojet, and ideal turbofan engines.

A thermodynamic cycle analysis was performed to compare the relative performances of the conventional engine and the turbine-burner engine with different combustion options for both turbojet and turbofan configurations. Turbine-burner engines were shown to provide significantly higher specific thrust with no or only small increases in thrust specific fuel consumption compared to conventional engines [18].

Durmuş and Akyuz [19], investigated parametric cycle analysis of a turboprop engine. Performance parameters such as specific fuel consumption (SFC), specific thrust, propulsive efficiency, thermal efficiency, overall efficiencies were calculated according to the pressure ratios and temperature (enthalpy) changes in reference stations. The overall engine efficiency obtained from multiplying thermal efficiency by propulsive efficiency occurs at low turbine inlet temperature and high compression ratio conditions.

Moore [20], examined the published literature on the ideal cycle for the scramjet engine including six parametric measures common to the ideal engine cycle analysis for turbojets and turbofans his research project. Specific thrust, fuel-to-air mass flow ratio, thrust specific fuel consumption, thermal, propulsive, and overall all efficiencies as well as a seventh parameter, thrust flux, across a range of free stream Mach numbers at various constant combustion Mach numbers and altitudes were evaluated. The results revealed that the new, seventh parametric measure, thrust flux, is a better indicator of at what flight Mach number the scramjet engine thrust will peak rather than the formerly assumed parametric measure, thrust specific fuel consumption.

Montgomerie [21], reported the development of an advanced engine for a UAV. The tool used for the engine thermodynamic cycle evaluations had exclusively been the GasTurb computer program. The types of bypass turbofan engines were studied in cases where afterburning is on or off. The final result consisted of the thrust and fuel consumption tables for different Mach numbers and altitudes valid for the fixed cycle engine. Bayir and Alquadah [22], compared of "F100-PW-229 and F110-GE-129 engines used in F-16. As a result of their analysis, F-16 It has been seen that the F100-PW-229 engine gives the best thrust performance for the lowest BPR value targeted in the engines.

Nordqvist and et al. [23], presented a design for a new turbofan engine intended for a conceptual supersonic business jet expected to enter service in 2025. The objective of their study was to perform a preliminary design of a jet engine, complying with a set of specifications. The thermodynamic analysis and optimization had been carried out using the Numerical Propulsion System Simulation(NPSS) code, where the cycle parameters such as fan pressure ratio, overall pressure ratio, turbine inlet temperature and bypass ratio. With the cycle selected, and the fluid properties at the different flow stations known, the component aerodynamic design, sizing and efficiency calculations were performed using MATLAB.

In this study, performance analysis of the engine according to the parameters determined by parametric cycle analysis in separate exhaust streams and afterburner turbofan engines were analyzed. There are many studies on non-design and design point for engine types in the literature. The effects of bypass ratio and Mach numbers on performance were examined in the literature; however, there was rate information about the compressor pressure ratio in addition to these parameters. Therefore, this study aims to examine the effect of bypass ratio, Mach number and compressor pressure ratio parameters on engine performance and interpret them. The value of the Mach number was determined as (0.6, 2.5) interval in order to observe the subsonic and upper sonic changes. The effects of compressor compression ratio and Mach number on efficiency were calculated and expressed graphically. The changes in specific thrust, specific fuel consumption, fuel-air ratio and efficiency were observed.

2. Material and Methods

In the turbofan engine, the incoming air is captured by the engine inlet. Some of the incoming air passes through the fan and continues on into the core compressor and then the burner, where it is mixed with fuel and combustion occurs. The hot exhaust passes through the core and fan turbines and then out the nozzle, as in a basic turbojet. The rest of the incoming air passes through the fan and bypasses, or goes around the engine, just like the air through a propeller. The air that goes through the fan has a velocity that is slightly increased from free stream. So, a turbofan gets some of its thrust from the core and some of its thrust from the fan [24]. The schematic diagram of the separate exhaust flow and afterburner turbofan engine with station numbers is shown in Figure 1.

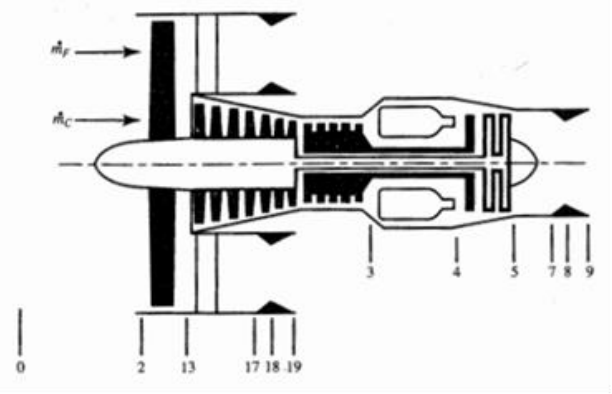

Fig. 1. Station numbering of turbofan engine [25]

0-Free stream flow, 2- Fan inlet, 3- Compressor outlet, 4-Combustion chamber inlet,

5-Combustion chamber outlet, 7-Nozzle inlet, 8-Exhaust nozzle throat area, 9-Nozzle outlet,

13-Fan outlet, 17- Bypass nozzle inlet, 18-Bypass nozzle throat area, 19-Bypass nozzle outlet

Performance cycle analysis is also known as off-design analysis. In this presented study, parametric cycle analysis was performed with Python code. Engine input parameters and parametric cycle input/output parameters were given Table 1 and Table 2, respectively.

All calculation algorithms were used and optimized using by appropriate numerical methods. Aircraft engine's fuel-air ratio (f) is the ratio of the masses flow of fuel and air. Indicates how much air must be mixed with jet fuel for a jet engine to run. Specific thrust ($F/\dot{m}_0$) is defined as the thrust of an engine per unit air mass flow rate in the Eq. (1), [26].

Table 1. Engine input values

C_{pc}=0.240 Btu/(lbm.°R)	γ_c=1.4	T_0=390 °R	π_{dmax}=0.98
h_{PR}=18400 Btu/lbm	e_c=0.90	e_f=0.89	e_t=0.91
π_n= π_{fn}=0.98	C_{pt}=0.295 Btu/(lbm.°R)	η_m=0.99	η_b=0.99
π_b=0.98	T_{t4}=3500 °R	γ_t=1.3	η_{AB}=0.95
C_{pAB}=0.295 Btu/(lbm.°R)	T_{t7}=4000 °R	γ_{AB}= γ_{DB} =1.3	π_{AB}=0.94
T_{t17}=4000 °R	C_{pDB}=0.295 Btu/(lbm.°R)	π_{DB}=0.94	η_{DB}=0.95

Table 2. Engine input and output parameters

Parametric cycle inputs (on design)		**Parametric cycle outputs (on design)**	
Flight conditions	M_0,P_0,T_0,CTOL,CTOH	**Thrust**	F/ $\dot{m}_0$
Fuel properties	h_{PR}	**Thrust specific fuel consumption**	S
Pressure ratios	π_b, π_{dmax}, π_n, π_f, π_{nF}, π_{cL}, π_c	**Propulsive efficiency**	η_p
Polytropic efficiencies	η_f, η_{cL}, η_{cH}, η_{tH}, η_{tL}	**Thermal efficiency**	η_{th}
Component efficiencies	η_b, η_{mL}, η_{mH}, η_{mPL}, η_{mPH}	**Overall efficiency**	η_o
Others	α, T_{t4}, $\dot{m}_0$	**Component behavior**	τ_f, τ_{cL}, τ_{cH}, τ_{tH}, τ_{tL}, τ_λ, f, η_f, η_{cL}, η_{cH}, η_{tH}, η_{tL}, M_9, P_{t9}/P_9, P_9/P_0, T_9/T_0, M_{19}, P_{t19}/P_{19}, P_{19}/P_0, T_{19}/T_0

$$\frac{F}{m_0} = \frac{1}{1+\alpha}\frac{a_0}{g_c}\left[(1+f+f_{AB})\frac{V_9}{a_0} - M_0 + (1+f+f_{AB}))x\frac{R_{AB}}{R_C}\frac{\frac{T_9}{T_0}}{\frac{V_9}{a_0}}\frac{1-\frac{P_0}{P_9}}{\gamma_C}\right] + \frac{\alpha}{1+\alpha}\frac{a_0}{g_C}\left[\frac{(1+f_{DB})V_{19}}{a_0} - M_0 + (1+f_{DB})x\frac{R_{DB}}{R_C}\frac{T_{19}/T_0}{V_{19}/a_0}\frac{1-P_0/P_{19}}{\gamma_C}\right] \tag{1}$$

Thrust specific fuel consumption (S or TSFC) is the rate of fuel use by the propulsion system per unit of thrust produced and is written in Eq. (2) form as,

$$S = \frac{f+f_{AB}+\alpha f_{DB}}{(1+\alpha)(F/m_0)} \tag{2}$$

Propulsive efficiency (η_P), is a measure of how effectively engine power is used to power the aircraft. In equation form (Eq. 3-Eq. 4), this is written as

$$\eta_P = \frac{2M_0\left[\frac{(1+f+f_{AB})V_9}{a_0}+\frac{\alpha(1+f_{DB})V_{19}}{a_0}-(1+\alpha)M_0\right]}{\left[(1+f+f_{AB})\left(\frac{V_9}{a_0}\right)^2+\alpha(1+f_{DB})\left(\frac{V_{19}}{a_0}\right)^2-(1+\alpha)M_0^2\right]} \tag{3}$$

$$\eta_{TH} = \frac{a_0^2\left[(1+f+f_{AB})\left(\frac{V_9}{a_0}\right)^2+\alpha(1+f_{DB})\left(\frac{V_{19}}{a_0}\right)^2-(1+\alpha)M_0^2\right]}{2h_{PR}(f+f_{AB}+\alpha f_{DB})} \tag{4}$$

Overall efficiency (η_O), the ratio of the thrust power to the rate at which thermal energy is made available by the fuel and it is equal to the product of the thrust efficiency and the thermal efficiency, Eq.(5)

$$\eta_O = \eta_{TH}\eta_P \tag{5}$$

3. Results and Discussion

The effect of bypass ratio (alfa) and Mach number was studied for specific thrust values. These plots are shown in Fig 2. In order to see both subsonic and supersonic values, the change between 0.6 - 2 Mach number was examined. According to this figure, increasing the Mach number Specific thrust values increase with the decrease of bypass ratio. As the bypass ratio increases, the thrust increases, but the specific thrust decreases as seen in the figure. This is because specific thrust (thrust per airflow) decreases due to the large amount of total mass flow processed by the engine similar to Dankanich and Peters's study [6]. The maximum value of the particular thrust in the specified range is its value at alpha = 3 and Mach number = 1.8.

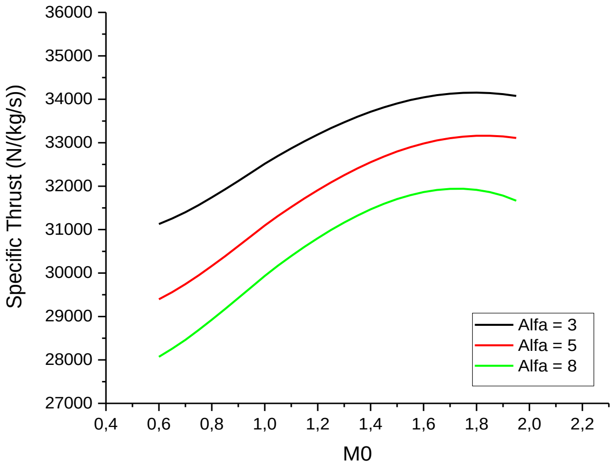

Fig. 2. The variation of the specific thrust with bypass ratio

Fig 3 and Fig. 4 shows the variation of Mach number versus the TSFC and efficiency along with the bypass ratio. As seen in Fig 3, the TSFC value increases as the bypass ratio increases. With afterburning, more thrust is produced, but the required fuel consumption also increases.

The change of the efficiency of the turbofan engine depending on the bypass ratio and Mach number (Fig. 4) shows that flying at high speeds increases the overall efficiency of the engine. In addition, the bypass ratio has a significant effect on the overall efficiency of the engine, and as the bypass ratio decreases, the overall efficiency of the engine increases for both subsonic and supersonic flow. Results were consistent with the studies of Swamy [13]. For this reason, when the bypass value is 3, efficiency is of the highest value. On the other, the lowest efficiency is when bypass value 8.

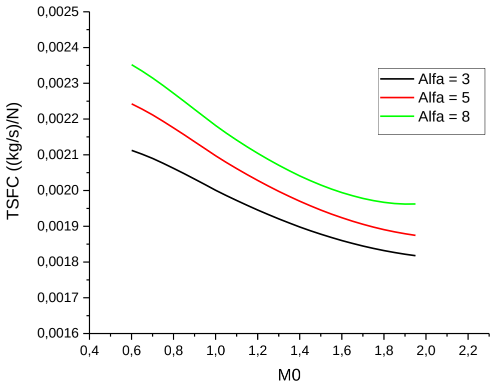

Fig. 3. The variation of the TSFC with bypass ratio

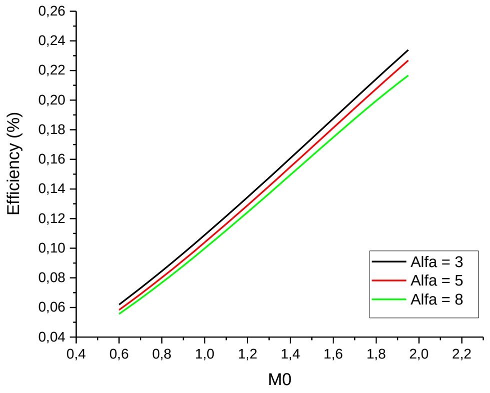

Fig. 4. The variation of the efficiency with bypass ratio

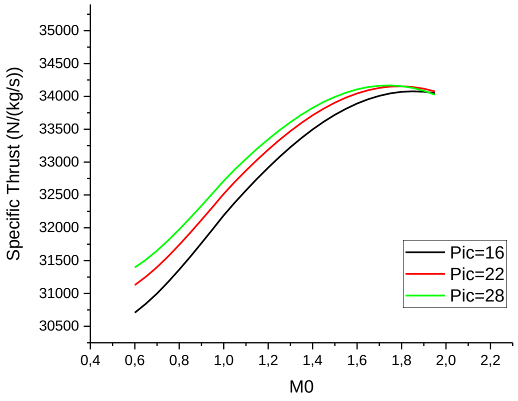

Fig. 5. The variation of the specific thrust with compressor pressure ratio

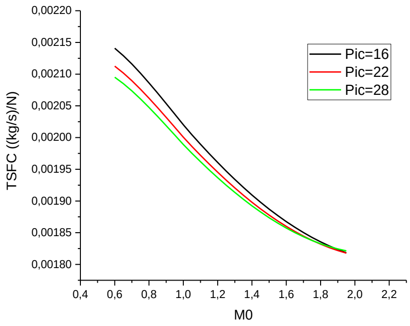

Fig. 6. The variation of the TSFC with compressor pressure ratio

When the specific thrust, thrust specific fuel consumption, fuel-air ratio and efficiency values are examined according to the compressor pressure ratio and Mach number change for the bypass ratio =3, the figures are obtained. The effect of Mach number and compressor pressure ratio on specific thrust is shown in Fig 5. According to this graph, the maximum specific thrust is high at high compressor pressure ratios. It is understood from this that high compression ratios should be preferred to obtain a good specific thrust value in subsonic flights [3]. As seen in Fig. 6, the specific fuel consumption decreases with the rise of compressor pressure ratio. Similar trend was obtained as in the literature [25]. According to Figure 7, the fuel-air ratio decreases as the flight Mach number increases. As the compressor pressure ratio is decreased, the fuel-air ratio increases [27]. The variation of the total efficiency value depending on the compressor pressure ratio and Mach number was obtained as in Figure 8. If we examine the graph, as the compressor pressure ratio and Mach number increase, the overall efficiency value increases. The results were consistent with the literature. Variation of efficiency at different Mach numbers was given in Table 3. This table shows that flying at high speeds of an engine with separate flow and afterburning increases the overall efficiency of the engine. The bypass ratio is highly influential on the overall efficiency of the engine, and as the bypass ratio decreases, the overall efficiency of the engine increases for both subsonic and supersonic flow [14].

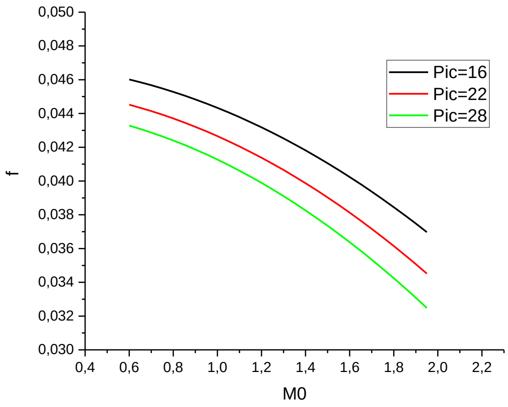

Fig. 7. The variation of the fuel-air ratio with compressor pressure ratio

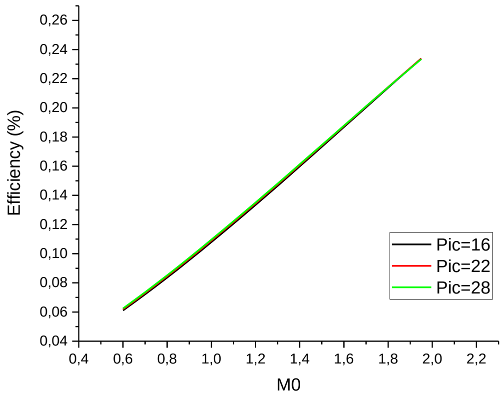

Fig. 8. The variation of the efficiency with compressor pressure ratio

Table 3. Variation of efficiency at different Mach numbers

Values	Efficiency of ref[14]	**Efficiency of this article**
$\Pi_f = 1.2, \alpha = 0.2$	[a] 0.1027 [b] 0.2005 [c] 0.2696	**[a] 0.1097** **[b] 0.2064** **[c] 0.2714**
$\Pi_f = 1.2, \alpha = 5$	[a] 0.0458 [b] 0.1386 [c] 0.2132	**[a] 0.0606** **[b] 0.1492** **[c] 0.2191**

[a] M0 = 0.8. [b] M0 = 1.5. [c] M0 = 2.

4. Conclusion

Numerical simulation of in split-flow and afterburner turbofan engines was performed using Python code in an attempt to evaluate the performance of the engine to determine how the engine will operate for different alfa conditions. The results are as follows:

- As the bypass ratio increased, the specific thrust value decreased. Maximum specific thrust was 34,154 at alpha=3 and Mach number=1.8. Maximum specific thrust value decreased by 6.48% when the alpha reached from 3 to 8. In addition, the minimum specific thrust value also decreases by 9.82%.
- While the total efficiency value increases with the increase of the compressor compression ratio, it decreases with the increase of the bypass ratio.
- Maximum specific fuel consumption value increases by 10.106% when the bypass ratio reached from 3 to 8. It is inversely proportional to the compressor pressure ratio. Maximum specific fuel consumption value decreases by 2.194% when the compressor pressure ratio reached from 16 to 28.
- Variation of specific thrust and fuel consumption was observed for different values of Mach number, alfa and bypass ratio.
- The thrust increased with increase in bypass ratio while the specific fuel consumption decreased with increase in bypass ratio

Although the work done in this study provides basic analysis of the turbofan engine cycle, many aspects of its performance need to be studied further. In future studies, it is recommended to carry out numerical studies involving all stations. Cycle analysis of aircraft propulsion systems can be solved by numerical programs (such as ANNs) and trained in programs.

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