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High-bypass Ratio, Separate-exhaust Turbofan engine: Study on Flight Mach Number and Inlet Temperature

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Keywords： Separate-exhaust turbofan engine, High-bypass ratio, Efficiency, thrust-specific fuel consumption, Mach Number, air temperature.

ABSTRACT

In this study, the effects of Mach Number and air temperature on high-bypass ratio, separate-exhaust turbofan engine efficiency, and fuel consumption were investigated. A coding method with real data was used and the comparison of results with valid data indicated that the error was below 2%. The results showed that with the increase of Mach Number from 0.1 to about 1.1, the overall efficiency and the propulsive efficiency increased, but the thermal efficiency was constant. Further, with the increase of Mach Number from 1.1 to 1.5, the three mentioned efficiencies decreased. The results showed that an increase in the Mach Number always increases the thrust-specific fuel consumption, but this increase is much more significant in the range of 1.3 to 1.5 and is associated with a sudden increase of 200%. It was observed that increasing the temperature from 210 K to 333 K had no tangible effect on any of the efficiencies and the efficiencies remained constant, but the fuel consumption increased with a constant slope of about %24.

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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 to be known as one of the fastest, safest and most appropriate forms of transportation and taken into consideration. In the gradual trend towards 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 air transportation has a major contribution to the countries' economic development, the administration strategies to reduce fuel consumption in the 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, aircraft systems designers in various fields such as structural design, aerodynamic design of aircraft, etc. have made many efforts in the last decades to reduce fuel consumption. Regarding the importance of the aircraft engine as a thrust generation system, the engine design subject is the most sensitive of the design process and this topic has caused the aircraft engine designers are constantly to improve the aircraft thrust system. Turbine engines in various industries are very important, so during the past decade some countries have conducted great efforts to design and construct air and land turbine engines this issue reflects the high will and tendency in the countries' military industries to achieve native turbine engines. Simulation and modeling of gas turbine engines as one of the most complex dynamical systems available, always an attractive industry issue to improve the performance and development of new control techniques, has been considered. To analyze the performance of turbine engines in the design phase based on the aero-thermodynamic behavior of the engine and its components, the engine mathematical model is provided, and using it, the engine performance is simulated and evaluated. These designs and analyses include various components of the engine, and researchers have made extensive efforts to optimize its various parts, for this purpose, experimental and simulation methods have been widely used,

Research Background

According to the importance of fuel consumption in aircraft which was mentioned in the previous section, so much research has been performed about it and optimum use of fuel. Merrill and his colleagues (1973) could implement a general model of the turbofan engine thrust. Lu et al. (1999), have examined aircraft control, through changes in aircraft thrust forces. Thiery et al. (1999), have performed a theoretical analysis of environmental and energetic performance of very high temperature. Ikaza et al. (2000), have provided a design for the performance development and sustainability of aircraft engines. Svoboda (2000), has provided a large database of known turbofan engines until the time for the ratio of the two numbers 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. Bartel (2008) has presented a simple design for fuel consumption performance and two-shaft turbofan engine thrust. Yunusov et al. (2006), have offered a design to control aircraft engine thrust by using flight information aircraft engines of diagnostic devices. Boyce (2011) developed a new edition brings the Gas Turbine Engineering Handbook right up to date with new legislation and emerging topics to help the next generation of gas turbine professionals understand the underlying principles of gas turbine operation, the economic considerations and implications of operating these machines, and how they fit in with alternative methods of power generation. Burlamaqui Filho et al., (2012) provided a dynamic modeling nonlinear and control system for a turboshaft. Homaeifar et al. (1994) have presented a method for improving turbofan engine performance using a general algorithm method. Zarepour, and Khani Aminjan (2018) modeled the thrust and specific fuel consumption for a hypothetical turbofan engine. Emine et al. (2024) in their study focused on analyzing the thermodynamic performance outcomes of the ammonia-fueled turbofan engine. It was calculated how much improvement could be achieved in the amount of emissions that occur in the case of using ammonia and kerosene. It was determined that the combustion chamber (CC) has the greatest improvement potential of the turbofan. In Baklacioglu, and Cavcar's study (2014), a new aero-propulsive model (APM) was derived from the flight manual data of a transport aircraft using Genetic Algorithms (GAs) to perform accurate trajectory predictions. The proposed GA model successfully predicted the trajectory for the descent phase, which was not possible in previous models. Goulos et al. (2016,2016) developed a tool for separate-jet exhaust system design and analysis, and the method was initially been validated on a small-scale turbine-powered simulator (TPS) nacelle. Xiong et al. (2012) performed optimization design for a separate exhaust system based on parallel multi-objective genetic algorithm and numerical simulation. Qiang (2013) developed the design method and carried out integration for the nacelle and exhaust system.

New Aspects of the Present Study and its Objectives

The research on high bypass ratio turbofan mainly concentrates on two aspects. On the one hand, the improvement in the performance of components, such as compressor, combustor, and so on, is used to improve the thermal efficiency of the engine and on the other hand, the study on increasing the bypass ratio of a civil turbofan engine is conducted at the same time. The key innovation of the current research is to study the effects of Mach number and air temperature entering the engine on thrust specific fuel consumption (TSFC), engine thermal efficiency (η_{th}), engine propulsive efficiency(η_P) and engine overall efficiency (η_O) in a high-bypass ratio, separate-exhaust turbofan engine. In studying the performance of each engine, having the performance specifications in the reference state, which is one of the essential requirements, checking the performance of an engine by changing the desired parameters, the performance parameters of the engine are calculated and the performance specifications are obtained in new conditions. Turbofan engines are one of the main engines in the aviation industry, so their analysis and modeling are necessary to achieve higher efficiency.

DEFINITION OF THE STUDIED ENGINE AND ITS DIFFERENT SECTIONS

Figure 1 shows the schematic of the high-bypass ratio, separate-exhaust turbofan engine, and its various components:

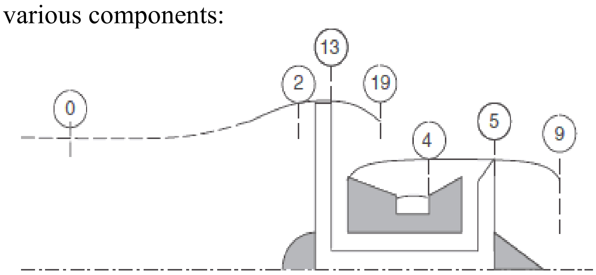


Fig. 1. The schematic image of high-bypass ratio,

separate-exhaust turbofan engine, ("*Farokhi, Saeed. Aircraft propulsion: cleaner, leaner, and greener. John Wiley & Sons, 2021*").

In Table 1, the different parts of Figure 1 are introduced:

Table 1. Definition of different parts of the engine station number

Engine station number	Description
0	Undisturbed airflow
2	Airflow through fan
4	Burnt gasses leaving the combustion chamber, burnt gasses entering the high-pressure turbine (HPT)
5	Further expanded gasses leaving LPT and entering the nozzle
9	Engine nozzle outlet
13	Compressed air leaving the fan and entering the bypass nozzle
19	Bypass nozzle outlet

SOLVING METHOD AND GOVERNING EQUATIONS

In this section using the thermodynamic relations (2021), we have paid to the analysis of the high-bypass ratio, separate-exhaust turbofan engine by applying this relationship by using EES software (2020). A high-bypass ratio (separate-exhaust) turbofan engine is used in commercial airplanes and at the cruise condition, the flight and engine operating conditions data are as Table 2:

Table 2. Flight conditions in cruise mode

M_0	-	0.88	Flight Mach number
P_o	kPa	15	Flight pressure
T_o	°C	-40	Flight temperature
γ_c	-	1.4	Specific heat ratio of compressor gases
Cpc	J/kg.K	1004	Specific heat of compressor gases
π_d	-	0.995	Inletpressure ratio
π_f	-	1.6	Fan pressure ratio
e_f	-	0.90	Fan efficiency
α	-	8.0	Fan bypass ratio
π_{fn}	-	0.95	Fan nozzle convergent
π_c	-	40	Compressor pressure ratio
e_c	-	0.90	Compressor efficiency
τ_λ	-	8.0	Flight static enthalpy
c_{pt}	J/kg.K	1152	Specific heat of turbine gases
γ_t	-	1.33	Specific heat ratio of turbine gases
Q_R	kJ/kg	42000	Fuel heating value
π_b	-	0.95	Total pressure ratio
η_b	-	0.992	Burner efficiency
η_m	-	0.95	Mechanical efficiency
e_t	-	0.85	Turbine efficiency
π_n	-	0.98	Primary nozzle convergent

In Equation 1-38, the thermodynamic analysis related to the turbofan engine in Figure 1 and the calculation of specific fuel consumption and thermal, propulsive, and overall efficiencies is presented:

The speed of sound at the flight altitude is

$$a_0 = \left((\gamma_c - 1)C_{Pc}T_0\right)^{0.5} \quad (1)$$

The flight speed is

$$V_0 = M_0 * a_0 \quad (2)$$

The total pressure of flight is

$$P_{t0} = P_0\left[\left(1+\left(\frac{\gamma_c-1}{2}\right)M_0{}^2\right)^{\frac{\gamma_c}{\gamma_c-1}}\right] \quad (3)$$

The total temperature of the flight is

$$T_{t0} = T_0\left(1+\left(\frac{\gamma_c-1}{2}\right)M_0{}^2\right) \quad (4)$$

The total pressure at the engine face is

$$P_{t2} = P_{t0}\pi_d \quad (5)$$

The total temperature at the engine face is equal to flight total temperature since inlets are adiabatic

$$T_{t2} = T_{t0} \quad (6)$$

The fan exit total pressure is

$$P_{t13} = P_{t2}\pi_f \quad (7)$$

We calculate the fan exit total temperature from its efficiency, namely

$$\tau_f = \pi_c^{\left(\frac{\gamma_c-1}{\gamma_c e_f}\right)} \quad (8)$$

The total temperature at the fan exit is

$$T_{t13} = T_{t2}\tau_f \quad (9)$$

The fan nozzle exit total pressure is

$$P_{t19} = P_{t13}\pi_{fn} \quad (10)$$

The nozzle exit static pressure is

$$P_{19} = \frac{P_{t19}}{\left(1+\frac{\gamma_c-1}{2}\right)^{\frac{\gamma_t}{\gamma_c-1}}} \quad (11)$$

The fan nozzle exit static temperature is

$$T_{19} = \frac{T_{t13}}{1.2} \quad (12)$$

The speed of sound at the fan nozzle exit is

$$a_{19} = \left((\gamma_c - 1)C_{pc}T_{19}\right)^{0.5} \quad (13)$$

The effective velocity at the fan nozzle exit is defined as

$$V_{19eff} = V_{19} + \frac{a_{19}^2\left(1-\frac{P_0}{P_{19}}\right)}{\gamma_c V_{19}} \quad (14)$$

The compressor exit total pressure is

$$P_{t3} = P_{t2}\pi_c \quad (15)$$

For compressor,

$$\tau_c = \pi_c^{\left(\frac{\gamma_c-1}{\gamma_c e_c}\right)} \quad (16)$$

The exit total temperature is

$$T_{t3} = T_{t12}\tau_c \quad (17)$$

The burner exit total pressure is

$$P_{t4} = P_{t3}\pi_b \quad (18)$$

The burner exit total temperature is

$$T_{t4} = \frac{C_{pc}T_0\tau_\lambda}{C_{pt}} \quad (19)$$

The fuel-to-air ratio is calculated from the energy balance across the burner,

$$f = \frac{C_{pt}T_{t4} - C_{pc}T_{t3}}{Q_R\eta_b - C_{pt}T_{t4}} \quad (20)$$

To get the total temperature at the turbine exit,

$$T_{t5} = T_{t4} - \left(\frac{C_{pc}(T_{t3}-T_{t2}) + aC_{pc}(T_{t3}-T_{t2})}{\eta_m(1+f)C_{pt}}\right) \quad (21)$$

To calculate the turbine exit total pressure, we use the polytropic efficiency e_t

$$\pi_t = \tau_t^{\left(\frac{\gamma_t}{e_t(\gamma_t-1)}\right)} \quad (22)$$

For turbine,

$$\tau_t = \frac{T_{t5}}{T_{t4}} \quad (23)$$

The turbine exit total pressure is

$$P_{t5} = P_{t4}\pi_t \quad (24)$$

The nozzle exit total pressure is

$$P_{t9} = P_{t5}\pi_n \quad (25)$$

We calculate *P9* based on P_{t9} and the choked exit condition according to

$$P_9 = \frac{P_{t9}}{\left(\frac{\gamma_t+1}{2}\right)^{\left(\frac{\gamma_t}{\gamma_t-1}\right)}} \quad (26)$$

The nozzle exit static temperature is

$$T_9 = \frac{T_{t5}}{\frac{\gamma_t+1}{2}} \quad (27)$$

The speed of sound at the nozzle exit is

$$a_9 = \left((\gamma_t - 1)C_{pt}T_9\right)^{0.5} \quad (28)$$

The effective exhaust speed is

$$V_{9eff} = V_9 + \frac{a_9^2\left(1-\frac{P_0}{P_9}\right)}{\gamma_t V_9} \quad (29)$$

The fan net thrust is

$$F_{n-fan} = a\dot{m}_0 V_{19eff} - a\dot{m}_0 V_0 \quad (30)$$

Non dimensional specific core trust is

$$NDS\ core\ trust = \frac{F_{n-fan}}{(1+a)\dot{m}_0 a_0} \quad (31)$$

In the above equations,

$$V_9 = a_9 \ and\ , V_{19} = a_{19} \quad (32)$$

Fan trust,

$$F_{fn} = \frac{a(V_{19eff} - V_0)}{a_0} \quad (33)$$

Core trust,

$$F_{cor} = \frac{(1+f)V_{9eff} - V_0}{a_0} \quad (34)$$

The thrust-specific fuel consumption is

$$TSFC = \frac{f}{a_0(1+a)(F_{fn}+F_{cor})} \quad (35)$$

Thermal efficiency is

$$\eta_{th} = \frac{aV_{19eff}^2 + (1+f)V_{9eff}^2 - (1+a)V_0^2}{2f\,Q_R} \quad (36)$$

Propulsive efficiency is

$$\eta_p = \frac{2(F_{fn}+F_{cor})(1+a)a_0V_0}{aV_{19eff}^2 + (1+f)V_{9eff}^2 - (1+a)V_0^2} \quad (37)$$

The overall efficiency is the product of the thermal and propulsive efficiency,

$$\eta_0 = \eta_{th} \cdot \eta_p \quad (38)$$

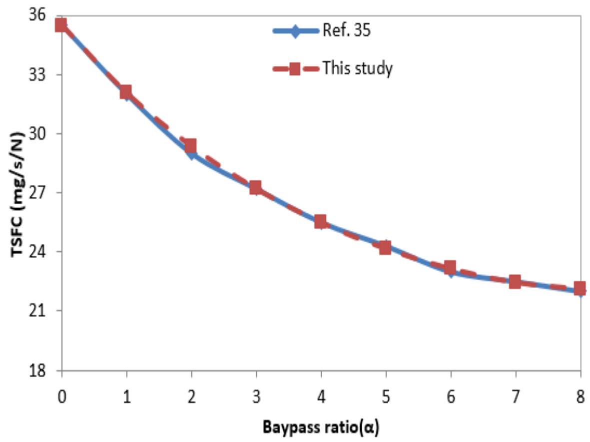
VALIDATION OF RESULTS

Validating the results and ensuring their correctness is the main part of any research work. In this study, the results of bypass ratio effects on specific fuel consumption and propulsion efficiency have been compared with Ref 35. As can be seen in Table 3 and Figure 2, the results of the current study have a very high accuracy and the error percentage is less than 2%.

Note: In this paper, Ref.35 is "*Farokhi, Saeed. Aircraft propulsion: cleaner, leaner, and greener. John Wiley & Sons, 2021*".

Table 3. Comparison of the results of the present study with Ref. 35

α	TSFC (mg/s/N) Ref.35	TSFC (mg/s/N) Present study	Error (%)	η_p (%) Ref.35	η_p (%) Present study	Error (%)
0	35.5	35.46	0.11267	44	44.35	0.79545
1	32	32.03	0.09375	49	48.71	0.59183
2	29	29.33	1.13793	54	53.02	1.81481
3	27.2	27.18	0.07353	58	57.35	1.12069
4	25.5	25.47	0.11765	61	61.73	1.19672
5	24.3	24.14	0.65844	66	66.22	0.33333
6	23	23.13	0.56522	71	70.82	0.25352
7	22.5	22.44	0.26666	76	75.45	0.72368
8	22	22.11	0.50000	80	79.80	0.25000



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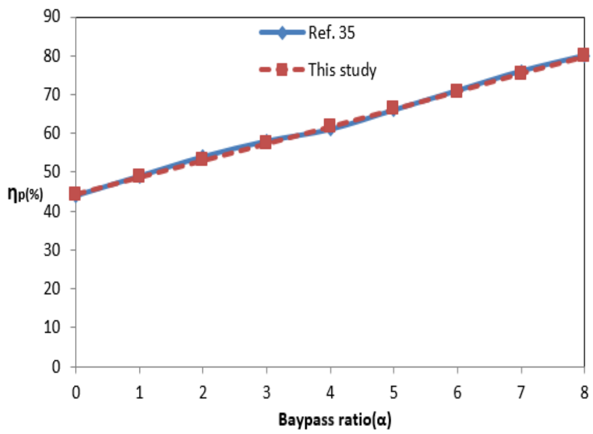

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Fig. 2. Comparing the results of the present study with Ref 35 in terms of bypass ratio. A: Special fuel consumption. B: Propulsion efficiency.

In Ref.35, the effects of bypass ratio on thermal efficiency, propulsion efficiency, overall efficiency, and thrust-specific fuel consumption have been studied. According to the results of Table 3 and Figure 2, which indicate the high accuracy of the present study, we follow Ref.35 and study the effect of new parameters including flight Mach number and ambient air temperature on the key parameters of the engine.

STUDY ON MACH NUMBER EFFECTS

When the plane reaches an altitude of 7,000-9,000 meters (25,000-30,000 feet), they compare their speed with the Mach number and express it as a percentage of the speed of sound. When the plane approaches the speed of sound, sound waves are created which cause aerodynamic problems. Therefore, the maximum Mach Number for airplanes is determined by the pilot's reference for flight speed. The effects of Mach Number on engine performance is an interesting and of course vital study. In this section, the effects of Mach number changes are studied. The range of Mach Number change is considered from 0.1 to 1.5 because it is a wide range and it is possible to have a more detailed study on the effects of Mach Number change on engine performance, and this range has been used in valid studies including Liew, K. H., et al. (2005). As can be seen in Figure 3 and Table 4, with the increase of Mach Number from 0.1 to about 1, the overall efficiency and propulsive efficiency increase, but the thermal efficiency of displacement is constant. Further, with the increase of Mach Number up to 1.5, all efficiencies decrease. The results show that the increase in Mach Number has a greater effect on the propulsive efficiency, such that with the increase in Mach Number from 0.1 to 1.1, the propulsive efficiency increases by about 418%. However, increasing the Mach Number from 1.1 to 1.5 causes a 50% reduction in propulsive efficiency. In addition, the results show that even though increasing the Mach Number always increases the thrust-specific fuel consumption, this increase is much more significant in the range of 1.3 to 1.5. In this range, the thrust-specific fuel consumption is associated with a sudden increase of 200%.

In the analysis of the results, it should be said that according to equation 2, increasing the Mach Number increases the flight speed, or in other words, increasing the speed of the air entering the engine, so according to equations 33 and 34, it will decrease the fan thrust and the core thrust. According to equation 35, the reduction of the fan thrust and the core thrust will lead to an increase in the special fuel consumption of the thrust. Equation 36 also indicates that increasing flight speed has an effect on thermal efficiency and causes it to decrease. The effect of speed increase on propulsive efficiency is a bit more complicated because if you pay attention to equation 37, you can see that propulsive efficiency is affected by flight speed core thrust and fan thrust. Increasing the Mach Number increases the flight speed, but decreases the thrust of the fan and the thrust of the core. Therefore, the effect of the Mach Number on the propulsive efficiency depends on the interaction of the effects on the flight speed and the thrust of the fan and the core. Up to Mach Number 1.2, the effect of increasing the flight speed has overcome the decrease in thrust, and the propulsive efficiency has an increasing trend, but for Mach Number higher than 1.2, the effects of decreasing the thrust have overcome the increase in speed, and therefore, it can be seen that for Mach Number 1.2 above, there is a decreasing trend in propulsive efficiency. According to equation 38, overall efficiency depends on the product of thermal and propulsive efficiency. On the other hand, since the propulsive efficiency is much more impressive than the thermal efficiency, therefore, the overall efficiency change trend is more influenced by the propulsive efficiency and corresponds to its trend. It should be noted that although increasing the Mach Number to up to 1.2 increases the thermal efficiency and overall efficiency, once the aircraft reaches sonic speed shockwaves can significantly impact commercial aircraft in various ways. Shock waves formed by supersonic flow can distort optical systems on aircraft, affecting laser systems (2023). Additionally, shockwaves at high speeds can affect aerodynamic performance, with swept angles on airfoils being one method to mitigate these effects (2021). Overall, shockwaves play a crucial role in the design, performance, and safety considerations of commercial aircraft.

Table 4. Investigating the effects of flight Mach Number

M_0	η_o(%)	η_p(%)	η_{th}(%)	**TSFC**(mg/s/N)
0.1	6	17	36.49	12
0.3	15	41	36.54	14.5
0.5	21	58	36.67	17.1
0.7	26	71	36.73	19.6
0.9	29	81	36.22	22.43
1.1	30	88	34.26	26.62
1.3	26	87	29.71	36.45
1.5	10	44	23.09	108

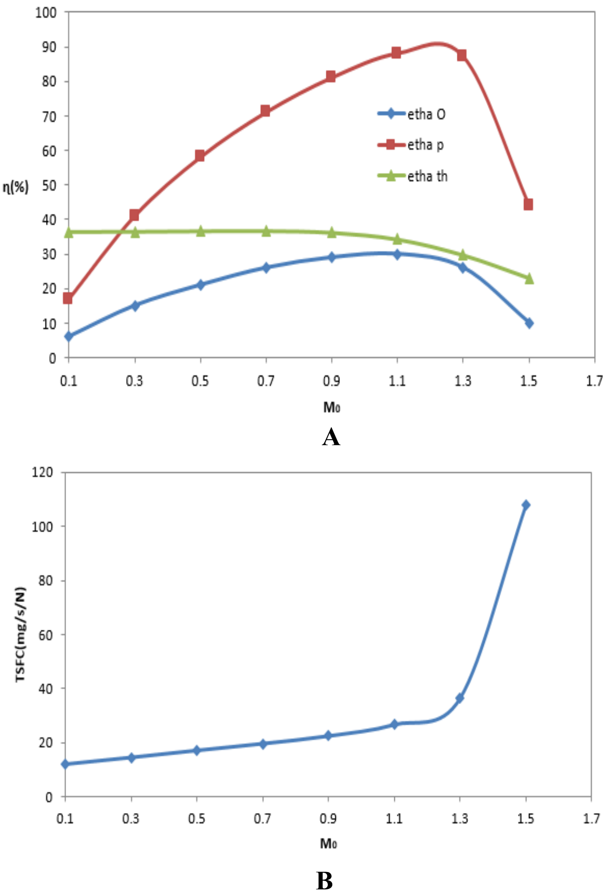


Fig. 3. Effects of Mach Number on: A. efficiency, B. specific fuel consumption

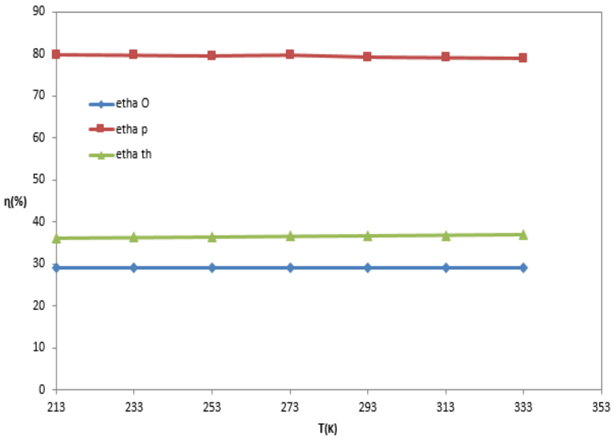
STUDY ON AIR TEMPERATURE EFFECTS

The temperature of the environment, whether hot or cold, regardless of the altitude of the airport, has a great impact on the performance of the aircraft, while having hot air and high altitude at the same time has a great impact on air transportation. Heat alone can reduce flight safety, cancellation, and other factors that must be controlled. All aircraft have specific instructions in different weather conditions, this instruction can include constant air temperature as well as pressure height. In 2017, temperatures of 49 degrees Celsius caused the cancellation of several Bombardier CRG flights in Phoenix, Arizona, because the temperature was outside the maximum operating temperature of the aircraft. Therefore, investigating the effects of air temperature on the performance of all types of air industry engines is a vital issue. In this section, the effects of the temperature of the air entering the engine have been evaluated, the results of which are presented in Figure 4 and Table 5. Commercial jet aircraft are designed to carry passengers safely and comfortably from one point to another. The external environments of the aircraft include taxiing, takeoff, cruise, and descent; outside temperature from below −55°C to over 50°C (2003). The range of air temperature changes is considered from 213 K to 333 K (-60 0C to +60 0C) because the flight of most airplanes is in this temperature range and in very rare cases it may be experienced outside this range [38]. It can be seen that increasing the temperature from 210 to 333 K has no tangible effect on any of the efficiencies and the efficiencies remain constant, but the special fuel consumption of the trust increases with a constant slope of about 24%.

In the analysis of the results, it can be argued that according to equations 1 and 2, increasing the temperature of the air entering the engine increases the speed of sound and flight speed, therefore, according to equations 33 and 34, it causes a significant decrease in fan thrust and core thrust. On the other hand, according to equations 4, 6, and 20, increasing the temperature causes a decrease in the ratio of fuel to air. Equation 35 shows that the specific fuel consumption of the thrust has a direct relationship with the fuel-to-air ratio and an inverse relationship with the speed of sound and core and fan thrust. Because the effect of increasing temperature on the reduction of fan thrust and core thrust is more significant compared to increasing the speed of sound and increasing the fuel-to-air ratio, so we see that with increasing temperature, specific fuel consumption increases. According to equation 36, the opposition of the effects of flight speed and fuel-air ratio causes the temperature increase, which does not have much effect on the thermal efficiency and only partially increases it. Contrasting the effects of temperature increase on sound speed, fan thrust core thrust and fuel-air ratio means that according to equation 37, we do not see a noticeable change in propulsive efficiency. Since the overall efficiency is equal to the product of the thermal and propulsive efficiency, and because these two efficiencies do not change significantly with the increase in temperature, there is no noticeable change in the overall efficiency either.

Table 5. Investigating the effects of the inlet temperature (ambient air temperature)

T(K)	η_o(%)	η_p(%)	η_{th}(%)	TSFC(mg/s/N)
213	28.95	79.96	36.20	21.2
233	28.99	79.80	36.32	22.1
253	29.03	79.64	36.44	23
273	29.06	79.84	36.57	23.9
293	29.10	79.32	36.69	24.7
313	29.13	79.15	36.81	25.5
333	29.17	78.99	36.93	26.3



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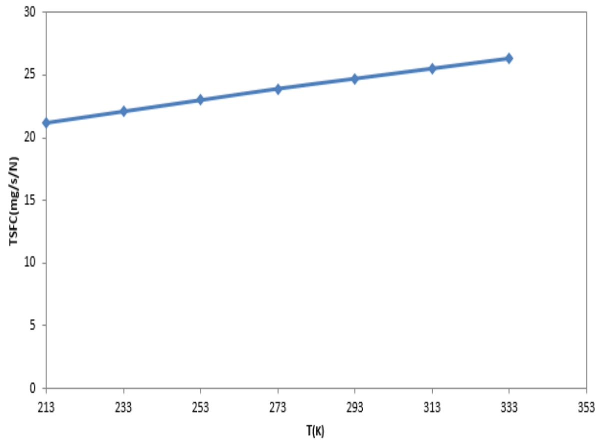

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Figure 4. Effects of air temperature on: A. efficiency, B. specific fuel consumption.

CONCLUSION

In this research, the effects of Mach Number and air temperature on the efficiency and thrust-specific fuel consumption of the high-bypass ratio, separate-exhaust turbofan engine were studied. In general, the results indicated that:

- With the increase of Mach Number from 0.1 to about 1, the overall efficiency and propulsive efficiency increased, but the thermal efficiency of the engine is constant. Further, with the increase of Mach number up to 1.5, all the efficiencies decreased.
- The results showed that the increase in Mach Number has a greater effect on the propulsive efficiency, such that with the increase in Mach Number from 0.1 to 1.1, the propulsive efficiency increased by about 418%. However, increasing the Mach Number from 1.1 to 1.5 causes a 50% reduction in propulsive efficiency.
- The results showed that even though increasing the Mach Number always increases the thrust-specific fuel consumption, this increase is much more significant in the range of 1.3 to 1.5 so in this range, the specific fuel consumption is associated with a sudden increase of 200%.
- It was observed that the increase in temperature from 210 to 333 K had no tangible effect on any of the efficiencies and the efficiencies remained constant, but the special fuel consumption of the trust increased with a constant slope of about 24%.

REFERENCES

Aminjan, Kiumars Khani, et al. "Study on inlet pressure and Reynolds number in pressure-swirl atomizer with spiral path." International Communications in Heat and Mass Transfer 137 (2022): 106231.

Aminjan, Kiumars Khani. "A Review on the change process and the evolution of aircraft engine air intake." International Journal of Mechanics and Design 4.1 (2018): 15-22.

Aminjan, Kiumars Khani, et al. "Comment on “DPM-LES investigation on flow field dynamic and acoustic characteristics of a twin-fluid nozzle by multi-field coupling method”." International Journal of Heat and Mass Transfer 217 (2023): 124678.

Balli, Ozgur, et al. "Exergetic and exergoeconomic analysis of an Aircraft Jet Engine (AJE)." International Journal of Exergy 5.5-6 (2008): 567-581.

Bartel, Matthias, and Trevor M. Young. "Simplified thrust and fuel consumption models for modern two-shaft turbofan engines." Journal of Aircraft 45.4 (2008): 1450-1456.

Baklacioglu, T., and M. Cavcar. "Aero-propulsive modelling for climb and descent trajectory prediction of transport aircraft using genetic algorithms." The Aeronautical Journal 118.1199 (2014): 65-79.

Boyce, Meherwan P. Gas turbine engineering handbook. Elsevier, 2011.

Burlamaqui Filho, F. A. C., et al. "Dynamic modeling nonlinear and control system for a turboshaft." 12th Pan-American Congress of Applied Mechanics. 2012.

Davoudi, Ali, et al. "Numerical simulation on heat transfer of nanofluid in conical spiral heat exchanger." Progress in Computational Fluid Dynamics, an International Journal 21.1 (2021): 52-63.

Doustdar, Mohammad Mahdi, and Kiumars Khani Aminjan. "Modeling the Thrust and Specific Fuel Consumption for a Hypothetical Turbojet Engine." International Journal of IC Engines and Gas Turbines 5.1 (2019): 45-52.

Doustdar, Mohammad Mehdi, Houman Alipour, and Maryam Aliakbari. "Estimating spray characteristics of the air-blast atomizer of a typical jet engine using definition of the new non-dimensional number K: numerical and experimental study." Tehnički vjesnik 29.1 (2022): 208-214.

Emine, O. Ğ. U. R., et al. "Performance Assessment of Ammonia as a Turbofan Engine Fuel During Various Altitude Levels." Energy (2024): 132714.

Farokhi, Saeed. Aircraft propulsion: cleaner, leaner, and greener. John Wiley & Sons, 2021.

Goulos, Ioannis, et al. "Aerodynamic design of separate-jet exhausts for future civil aero-engines—Part I: Parametric geometry definition and computational fluid dynamics approach." Journal of Engineering for Gas Turbines and Power 138.8 (2016): 081201.

Goulos, Ioannis, et al. "Aerodynamic design of separate-jet exhausts for future civil aero-engines—part ii: design space exploration, surrogate modeling, and optimization." Journal of Engineering for Gas Turbines and Power 138.8 (2016): 081202.

Homaifar, Abdollah, H. Y. Lai, and E. McCormick. "System optimization of turbofan engines using genetic algorithms." Applied Mathematical Modelling 18.2 (1994): 72-83.

Ikaza, Daniel, and Christian Rausch. "Thrust vectoring for eurofighter-the first steps." Air & Space Europe 2.1 (2000): 92-95.

Kalensky, Matthew, Matthew R. Kemnetz, and Mark F. Spencer. "Effects of shock waves on shack–hartmann wavefront sensor data." AIAA Journal 61.6 (2023): 2356-2368.

Kyprianidis, K. G., and Anestis I. Kalfas. "Dynamic performance investigations of a turbojet engine using a cross-application visual oriented platform." The Aeronautical Journal 112.1129 (2008): 161-169.

Lin, A. Q., et al. "Effective boundary conditions and numerical method for flow characteristics of aeroengine compressor at high Mach flight." Journal of Applied Fluid Mechanics 12.3 (2019): 845-855.

Liew, K. H., et al. Performance cycle analysis of a two-Spool, separate-exhaust turbofan with interstage turbine burner. No. E-15150. 2005.

Lu, Ping, and John J. Burken. "Controlling aircraft with engine thrust only: nonlinear challenges." Nonlinear Analysis: Theory, Methods & Applications 35.1 (1999): 21-35.

Mahmoodi, Mostafa, and Kiumars Khani Aminjan. "Numerical simulation of flow through sukhoi 24 air inlet." Computational Research Progress in Applied Science & Engineering (CRPASE) 3 (2017).

Merril, G. L. "Turbofan propultion for General Aviation." SAE Int J 32.3 (1973): 23-65p.

Milani, Samira Marami, Rahim Khoshbakhti Saray, and Mohammad Najafi. "Comparison of different optimized heat driven power-cycle configurations of a gas engine." Applied Thermal Engineering 179 (2020): 115768.

Mohammadzadeh, Kazem, et al. "Numerical investigation of anode channel clogging of a PEMFC with a realistic droplet size distribution." Journal of the Brazilian Society of Mechanical Sciences and Engineering 42 (2020): 1-13.

National Research Council, et al. "The airliner cabin environment and the health of passengers and crew." (2002).

Parhrizkar, Hamid, et al. "Optimization of S-shaped air intake by computational fluid dynamics." International Journal of Fluid Mechanics & Thermal Sciences 5.2 (2019): 36.

Peyvan, A., and A. H. Benisi. "Axial-flow compressor performance prediction in design and off-design conditions through 1-D and 3-D modeling and experimental study." Journal of Applied Fluid Mechanics 9.5 (2016): 2149-2160.

Puspitasari, Dewi, and Kasyful Warist Kiat. "SHOCKWAVE STUDY ON THE WINGS NACA 0012, NACA 64-206, AND NASA SC (2)-0706 WITH Λ= 15O AT 0.85 MACH NUMBER." Indonesian Journal of Engineering and Science 2.1 (2021): 025-032.

Wang, W. J., et al. "Influence of geometric parameters on overall performance of high bypass ratio turbofan nacelle and exhaust system." Journal of Applied Fluid Mechanics 13.6 (2020): 1959-1973.

Saadon, S., and MNA Mohd Isa. "SUSTAINABLE ASSESSMENT OF TURBOFAN ENGINE INTEGRATED WITH ORGANIC RANKINE CYCLE THROUGH EXERGETIC APPROACH." PERINTIS eJournal 10.2 (2020): 30-37.

Sepehrnia, Mojtaba, et al. "Experimental study, prediction modeling, sensitivity analysis, and optimization of rheological behavior and dynamic viscosity of 5W30 engine oil based SiO2/MWCNT hybrid nanofluid." Ain Shams Engineering Journal 15.1 (2024): 102257.

Svoboda, Charlie. "Turbofan engine database as a preliminary design tool." Aircraft design 3.1 (2000): 17-31.

Thiery, G., H. Simon, and S. Pascal. "Theoretical analysis of environmental and energetic performance of very high temperature." Thermodyn Sci 380 (1999): 442-81p.

Xiong, Jian, et al. "Aerodynamic optimization design of high bypass ratio separate-flow exhaust system based on parallel multi-objective genetic algorithm." Journal of Aerospace

Power 27.6 (2012): 1384-1390.

Yangaz, M. U., G. A. Çiftçioğlu, and M. A. N. Kadırgan. "Comparison of conventional and modified burners in performance with different fuels using a linear and a non-linear eddy-viscosity turbulence model." Journal of Applied Fluid Mechanics 12.6 (2019): 2069-2081.

Yarlagadda, Santosh. Performance analysis of J85 turbojet engine matching thrust with reduced inlet pressure to the compressor. MS thesis. University of Toledo, 2010.

Yunusov, S., Vl Labendik, and E. Kopytov. "Turbofan thrust control on flight information in aircraft engine diagnostic system." Ultragarsas/Ultrasound 60.3 (2006): 20-23.

Zarepour, Gholamreza, and Kiumars Khani Aminjan. "Modeling the Thrust and Specific Fuel Consumption for a Hypothetical Turbofan Engine." International Journal of IC Engines and Gas Turbines 4.1 (2018): 1-10.