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PERFORMANCE ANALYSIS OF HIGH BYPASS RATIO TURBOFAN AEROENGINE

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ABSTRACT

The turbofan engine had many developments in the past 60 years and becomes the common power plant employed in both civil airliners and military aircrafts. It combines the advantages of both of turboprop engines (high propulsive efficiency and thrust) and turbojet engines (high flight speed and altitude). To cope with the needs of high thrust forces that propel wide body airliner and increase of their payload and range as well as enlarging mauver capabilities of military aircrafts, successive developments of turbofan engines are needed. These developments in turbofan design have endeavors of larger thrust force, low noise and emission as well as better fuel economy. These goals were achieved by increasing of the bypass ratio (BR), fan pressure ratio (FPR), overall pressure ratio (OPR), turbine inlet temperature (TIT) as well as using new materials, production and cooling techniques for both turbines and combustion chamber. Such modifications led to improvements in thermal, propulsive and overall efficiencies, decreases in thrust specific fuel consumption (TSFC) and increase the specific thrust. This paper presents a parametric study and design point selection of a high bypass ratio turbofan engine (close to GEnx-1B70). This engine is one of the products of GE Aviation Company. Performance analysis is performed using MATLAB program codes.

INTRODUCTION

To move an airplane through the air, thrust is generated by some kind of propulsion system. Most modern airliners use turbofan engines because of their high thrust and good fuel efficiency. On this page, we will discuss some of the fundamentals of turbofan engines. Turbofan engine is the most modern variation of the basic gas turbine engine. As with other gas turbines, there is a core engine. In the turbofan engine, the core engine is surrounded by a fan in the front and an additional turbine at the rear. The fan and fan turbine are composed of many blades, like the core compressor and core turbine, and are connected to an additional shaft. As with the core compressor and turbine, some of the fan blades turn with the shaft and some blades remain stationary. The fan shaft passes through the core shaft for mechanical reasons. How does a turbofan engine work? 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. The ratio of the air that goes around the engine to the air that goes through the core is called the bypass ratio. Because the fuel flow rate for the core is changed only a small amount by the addition of the fan, a turbofan generates more thrust for nearly the same amount of fuel used by the core. This means that a turbofan is very fuel efficient. In fact, high bypass ratio turbofans are nearly as fuel efficient as turboprops. Because the fan is enclosed by the inlet and is composed of many blades, it can operate efficiently at higher speeds than a simple propeller. That is why turbofans are found on high speed transports and propellers are used on low speed transports. Low bypass ratio turbofans are still more fuel efficient than basic turbojets. Many modern fighter planes actually use low bypass ratio turbofans equipped with afterburners.

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They can then cruise efficiently but still have high thrust when dog fighting. Even though the fighter plane can fly much faster than the speed of sound, the air going into the engine must travel less than the speed of sound for high efficiency. Therefore, the airplane inlet slows the air down from supersonic speeds (Benson, 2014).

First Turbofan Engine

Rolls-Royce Conway was the first by-pass engine (or turbofan) in the world to enter service. Bypass ratio of about 25%. Average achieved thrust from 9,250 (Ib) to 20,250 (Ib).Major applications: Boeing 707, Douglas DC-8, Vickers VC10.A prototype was manufactured in January 1950 as the Conway RCo.2 (Clarke, 1960; Wenger 2014).

First Two Spool Engine

Bristol Siddeley Olympus turbojet engine was the first two spool axial flow turbojet engine .The yea of production is 1950.Average achieved dry thrust from 11,000(Ib) to 17,000 (Ib).Olympus MK201 develops 24,000(Ib) with Bristol Solar fully variable reheat. Major applications: Avro Vulcan and BAC TSR-2 (Clarke 1954; Clarke 1959).

First Afterburning Turbofan Engine

Pratt andWhitney's TF30 was the first dual-spool, afterburning turbofan engine to enter service with the military. The thrust force ranges from20,000-lb to 20,840-lb with afterburner. The program was launched in 1959 to develop a military engine with afterburning for sustained supersonic speeds. The first flight of the engine, designated TF30 by the military, was on December 21, 1964, in a twin-engine General Dynamics F-111A being developed for the Air Force. Major applications: General Dynamics F-111, LTV A-7A, B, C and Grumman F-14A (http://www.pw.utc.com/TF30_Engine.[Accessed 6/10/2014].; Global Security 2012).

First True Three-Spool Turbofan Engine

The Rolls-Royce RB211 is a family of high-bypass turbofan engines made by Rolls-Royce and capable of generating 37,400 to 60,600 pounds-force thrust. Originally developed for the Lockheed L-1011 (TriStar), it entered service in 1972 and was the only engine to power this aircraft type. The RB211 became the first true three-spool engine. The RB211 was officially superseded in the 1990s by the Rolls-Royce Trent family of engines, the conceptual offspring of the RB211.Rolls-Royce developed that the RB211 to provide greater thrust. By redesigning the fan and the IP compressor the engine's thrust reached 50,000 lbf (220 kN). The new version was designated RB211-524, and would be able to power new variants of the L-1011, as well as the Boeing 747.The RB211 series engines are also power plant options for the Boeing 757s and 767s aircraft. There are several iterations of the RB211 over its long history (Avioserv 2014).

Turbofan Engines ClassificationsAccording to Engine Bypass Ratio

A key parameter for classifying the turbofan is its bypass ratio, defined as the ratio of the mass flow rate of the bypass stream to the mass flow rate entering the core.

According to Low-Bypass Turbofans and Turbojets

In the higher regime of aircraft flight speed, the low supersonic range from Mach numbers above 1 up to 2 or 3, one finds the application of the simple turbojet (with no bypass stream) and the low-bypass turbofan engine (with a bypass ratio up to 2) (Encyclopædia Britannica 2014). The afterburner is added to this type of turbofan engines as a means of thrust augmentation by as much as 50 percent (Rolls-Royce plc 1986).

According to Medium-Bypass Turbofans, High-Bypass Turbofans, and Ultrahigh-Bypass Engines

Moving up in the spectrum of flight speeds to the transonic regime—Mach numbers from 0.75 to 0.9—the most common engine configurations are turbofan engines (Encyclopædia Britannica 2014).

According to Medium-bypass engines

Medium-bypass engines (with bypass ratios from 2 to 4) (Encyclopædia Britannica 2014).

According to High-bypass engines:

High-bypass engines (with bypass ratios from 5 to 8) (Encyclopædia Britannica 2014).

Ultrahigh-bypass engines, so-called UBEs (Geared turbofan engine)

Ultrahigh-bypass engines (with bypass ratios from 9 to 15 or higher). Ultrahigh-bypass engines (as shown in Fig.4) may have a gearbox between the drive turbine and the fan to simplify the design of the small-diameter turbine (with the attendant high rotative speed) without compromising the performance of the very large-diameter fan (with the attendant low rotative speed). Honeywell

TFE731, the Honeywell ALF 502/507, and the recent Pratt andWhitney PW1000G are examples of GTE (Geared turbofan engines) (Encyclopædia Britannica 2014).

According to the number of spools

Single Spool

The single-shaft turbofan is probably the simplest configuration, comprising a fan and high-pressure compressor driven by a single turbine unit, all on the same shaft. The SNECMA M53, which powers Mirage fighter aircraft, is an example of a single-shaft turbofan (Snecma 2009).

Double spool

Many turbofans have the basic two-spool configuration where both the fan and LP turbine (i.e., LP spool) are mounted on a second (LP) shaft, running concentrically with the HP spool (i.e., HP compressor driven by HP turbine). Higher overall pressure ratios can be achieved by either raising the HP compressor pressure ratio or adding an intermediate-pressure (IP) Compressor between the fan and HP compressor, to supercharge or boost the latter unit helping to raise the overall pressure ratio of the engine cycle to the very high levels employed today Called boosted (e.g., General Electric CF6,GE90andGEnxplus Pratt andWhitney JT9D andPW4000) (Hill et al.,1992).

Triple spool

Rolls-Royce chose a three spool configuration for their large civil turbofans (i.e., the RB211 and Trent families), where the intermediate pressure (IP) compressor is mounted on a separate (IP) shaft, running concentrically with the LP and HP shafts, and is driven by a separate IP (Hunecke 1997). Ivchenko Design Bureau chose the same configuration for their Lotarev D-36 engine, followed by Lotarev/Progress D-18Tand Progress D-436 (Ivchenko-Progress 2013). The Turbo-Union RB199 military turbofan also has a three spool configuration, as do the military Kuznetsov NK-25 and NK-321.

According to the flow type

Unmixed flow type turbofan engine

At this type of the turbofan engines the fan air is passed directly to the atmosphere without prior mixing with the core exhaust gases (separate nozzles), Fig. 2 (https: // www .faa.gov /regulations _policies/ handbooks _manuals/aircraft/media/FAA-H-8083-32-AMT-owerplant-Vol-1.pdf.[Accessed).

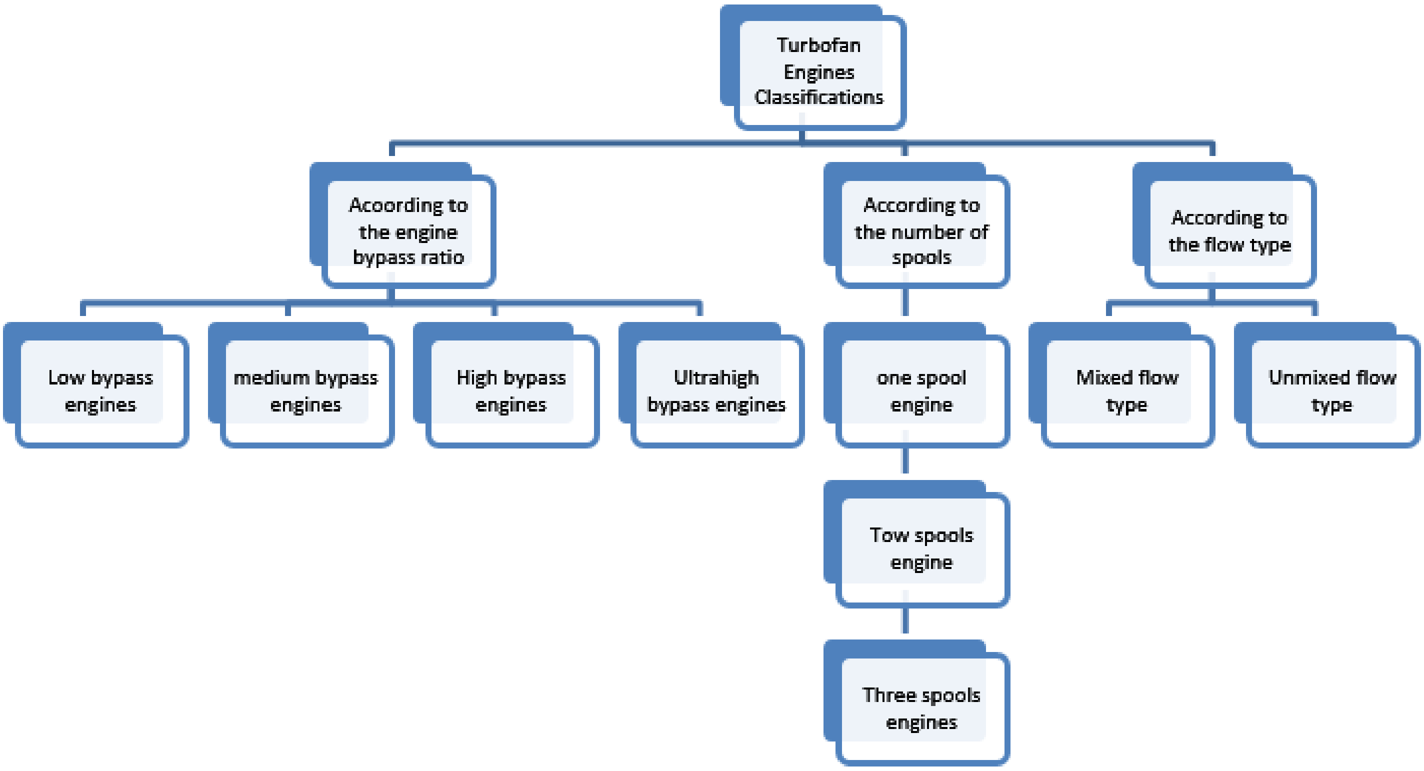


Fig. 1. Classification of Turbofan Engines

Mixed flow type turbofan engine

At this type of the turbofan engines the fan air is mixed with the core exhaust gases before it is discharged to the atmosphere (mixed or common nozzle), Fig. 3 (https: // www .faa.gov /regulations _policies/ handbooks _manuals/aircraft/media/FAA-H-8083-32-AMT-owerplant-Vol-1.pdf.[Accessed).

Fig. 2. Turbofan engine with separate nozzles fan and core (https: // www .faa.gov /regulations _policies/ handbooks _manuals/aircraft/media/FAA-H-8083-32-AMT-Powerplant-Vol-1.pdf.[Accessed 6/10/2014].)

The turbofan engine has undertaken magnificent developments over the past sixty years. This portion of the book aims to provide an overview of these developments.

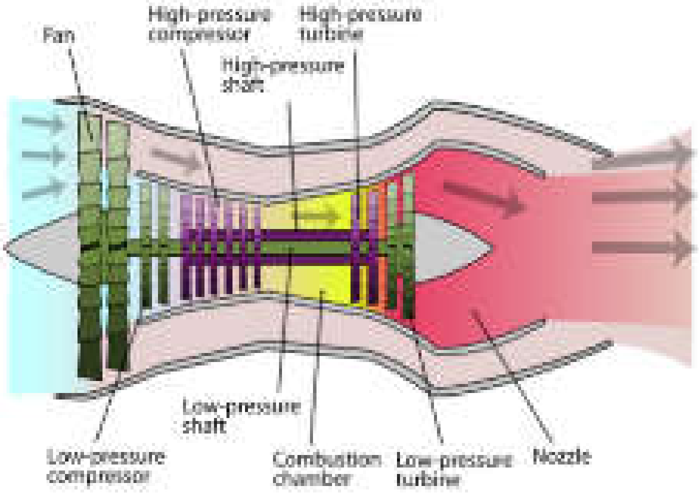


Fig. 3. Turbofan engine with mixed or common nozzle (Wikipedia, 2014)

Development of turbo fan engine

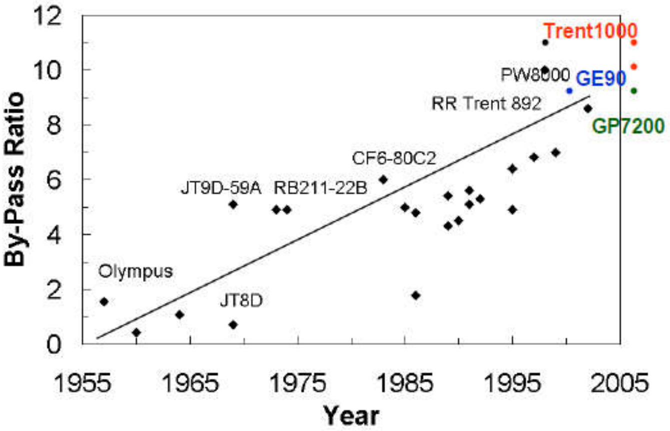


Fig. 4. Development of Turbofan Engine Bypass Ratio (Ballal and Zelina, 2003).

The Bypass Ratio

The growth of bypass ratios during the 1960s gave jetliners fuel efficiency that could compete with that of piston-powered planes. Pratt andWhitney and General Electric developed most of the very large high-bypass engines in the United States, which for the first time was besting the United Kingdom in engine design. Rolls-Royce also started the development of the high-bypass turbofan .Today; almost all jet engines have some bypass. Modern engines in slower aircraft, such as airliners, have bypass ratios up to 17:1[0]; in higher-speed aircraft, such as fighters, bypass ratios are much lower, around 1.5; and craft designed for speeds up to Mach 2 and somewhat above have bypass ratios below 0.5.(Fig. 4.)

Thrust

This is a measure of engine power. The data are available for both takeoff and cruise conditions. We chose to compare takeoff thrust [sea-level static condition (SLS), dry] for this survey because data are available for this operating condition. The figure below (fig.5) shows the progress of engine takeoff thrust (SLS dry condition) to date. Many military engines use afterburners to boost the takeoff thrust level as much as 80%. However, analyzing data for military jet engines with their afterburners turned off show that today's military engines are at least 20 times more powerful. These data also show a dramatic enhancement in thrust since the mid-1980s as a result of many factors. For example, in the civil sector the worldwide boom in air travel created a market need for super-large aircraft and high thrust engines to propel them. Also, in the United States, the IHPTET program initiated in October 1987 led to a coordinated effort between government and industry to significantly enhance military turbo propulsion capability. Advances in lightweight, high temperature composite materials and the computer revolution also made possible the optimization of many aerodynamic and structural design parameters.

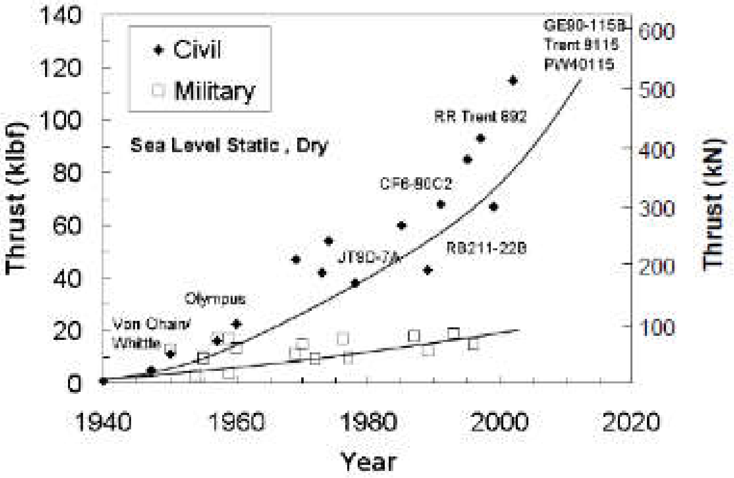


Fig. 5. Development of Turbofan Engine Thrust Force (Ballal and Zelina, 2003)

Thrust-to-Weight Ratio

Weight is the enemy of aircraft performance and fuel economy, and a lighter engine improves both. Therefore, engine (takeoff thrust/dry weight) ratio is a key design parameter. The following figure shows improvements in thrust-to-weight ratio (T/W). (Fig. 6.)

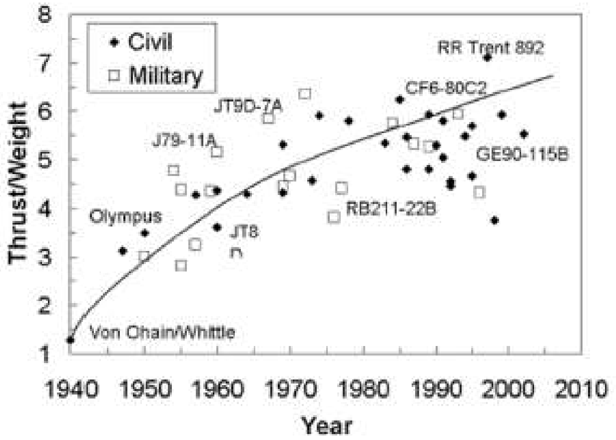


Fig. 6. Development of Thrust-To-Weight Ratio Turbofan Engine (Ballal and Zelina, 2003)

Overall Pressure Ratio

The combined fan and compressor performance is characterized by an overall pressure ratio (OPR). This value is the product of fan and core compressor pressure ratios. Higher OPR generally produces high thermal efficiency and lower TSFC.[0] Today's large civil turbofan engines are typically approaching a fan pressure ratio around 1.7.The Fig.7 shows the takeoff SLS OPR data for both military and civil engines.

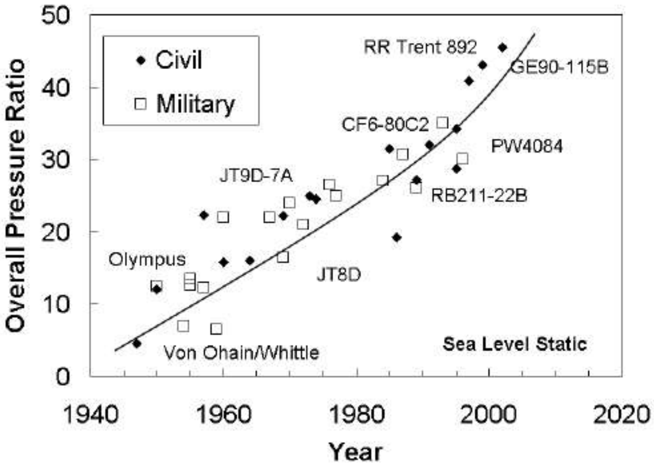


Fig. 7. Development of Turbofan Engine Overall Pressure Ratio (Ballal and Zelina, 2003)

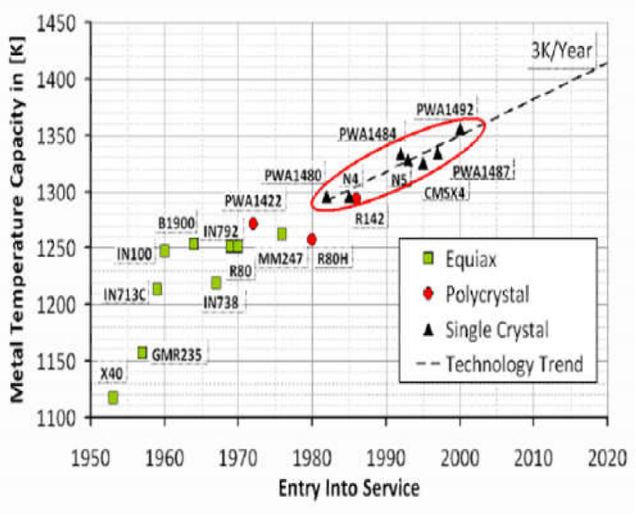


Fig. 8. Evolution of turbine material capability and future trend (Kyprianidi, 2011)

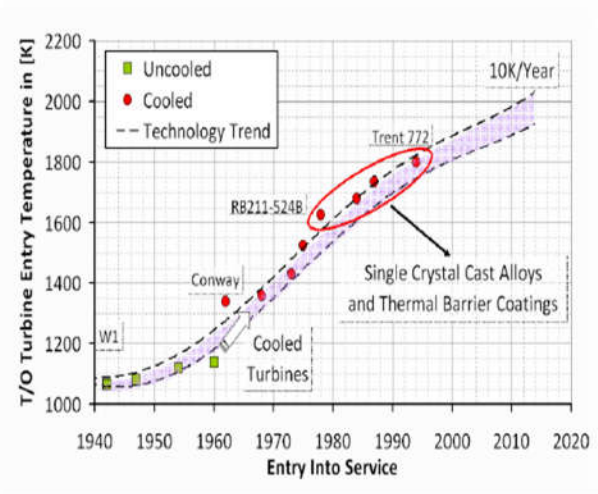


Fig.9. Evolution of turbine entry temperature and future trend (Kyprianidi, 2011)

It is observed that the most powerful civil engines of today are reaching a maximum OPR = 45. Such impressive achievements result from the extensive use of lightweight composite materials, computer-assisted structural design, and improved aerodynamics leading to lighter turbo machinery. Over the years, compressor designers have continued to pursue the strategy of increasing the stage pressure ratio. Clearly, it would save weight and parts if the compressor could develop the same pressure ratio in as few compressor stages as possible.

Turbine inlet temperature development

The evolution of turbine material capability over a period of 50 years is illustrated in Fig.8. As can be observed, only mild improvements have been achieved so far and this seems to be a continuing trend; the potential introduction of ceramics would form a major improvement in the field, but substantially more research is still required before realizing this. Despite the low improvement rate in turbine material technology (roughly 3 [K/year]) aero engine designs have seen substantial increases in T4 over the last 60 years (roughly 10 [K/year]); this is illustrated in Fig.9 for engines designed for long-haul applications. The main reason behind these improvements in T4 has been the introduction of cooling and Thermal Barrier Coatings (TBC) in turbine designs; Advances in manufacturing techniques have permitted turbine blades to be made with small and intricate air-cooling passages. This has decreased blade cooling air requirements and at the same time has enabled higher turbine inlet temperatures Other advances in turbine design include super-cooling of turbine airfoils, hollow Ceramic Matrix Composite (CMC) HPT vanes, and bonded dual-web turbine disks. These advances are leading to turbine designs with fewer airfoils, with significant reduction in blade cooling flow, and over 90% stage efficiencies (2011 Kyprianidis).

Specific Fuel Consumption

TSFC of an engine is inversely proportional to its overall efficiency (overall efficiency = propulsive efficiency × thermal efficiency). In terms of component parameters, low TSFC is achieved by an optimum combination of BPR, OPR, and turbine inlet temperature. The data for TSFC are available for both takeoff and cruise conditions (Mach 0.8, 35,000 ft). We chose to compare takeoff TSFC (SLS, dry) for this survey. The Fig. 10 shows TSFC vs. year trend for both military and civil engines (NASA 2013).

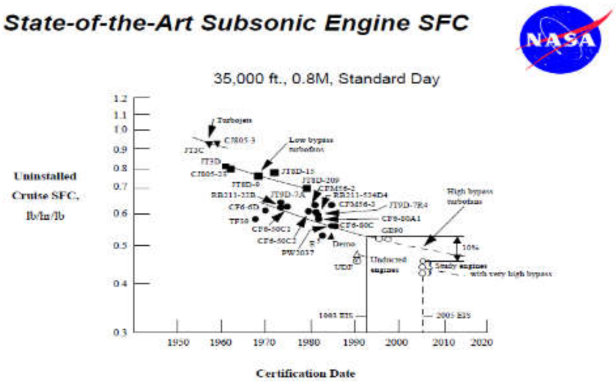


Fig. 10. TSFC vs. year trend (NASA, 2013)

PERFORMANCE ANALYSIS: PARAMETRIC STUDY andDESIGN POINTS SELECTION

Turbofan Engine Specifications

Table 1. Turbofan Engine Specifications (Aviation, 2014)

Engine Model	GEnx-1B70
Company	General Electric (USA)
Application	Boeing 787-8 Dreamliner
Certified (FAA)	March 31, 2008
Description	Two-Shaft High BPR TF
Weight (Dry)	6147,1 Kg
Width	3533,1 mm
Height	3484,9 mm
Overall Length	4950,5 mm
Intake/Fan Diameter	2.82m
Presence of FADEC	Yes
Max. takeoff thrust(5 min.)	(321.735KN)
fan speed (takeoff thrust(5 min.))	2,401 rpm
Max continuous thrust	295.8 KN
fan speed (Max continuous thrust)	2,319 rpm
π_{HPC}	23
Overall pressure ratio(Max. power)	43.5
Fuel Flow Rate(Takeoff) (Kg/s)	2.494
Fuel Flow Rate(Cruise) (Kg/s)	2.037
Bypass ratio(B)	9.1
Total air mass flow rate (Kg/s)(Takeoff)	1155.43
Bypass Air Flow Rate (Kg/s)	1041.03
Core Air Flow Rate (Kg/s)	114.399
Fuel Heating Value(KJ/Kg)	42555.066
Air Bleed (%)(stage 7)	3.3
Compressor stages	1F + 4L, 10H
Turbine stages	2H, 7L

The Laws Used In the Cycle Analysis

$$P_{oa} = P_a\left(1 + \frac{\gamma_c \quad 1}{2} M_a{}^2\right)^{\frac{\gamma_c}{\gamma_c - 1}}$$

$$T_{oa=}T_a\left(1 + \frac{\gamma_c \quad 1}{2} M_a{}^2\right)$$

In Diffuser (Air Intake)

$$P_{o1} = P_a\left(1 + \eta_d \frac{\gamma_c \quad 1}{2} M_a{}^2\right)^{\frac{\gamma_c}{\gamma_c - 1}}$$

$$T_{o1} = T_{oa} = T_a\left(1 + \frac{\gamma_c \quad 1}{2} M_a{}^2\right)$$

Fan Section

$$P_{o9} = P_{o1}\,\pi_f$$

$$T_{o9} = T_{o1}\left[1 + \frac{1}{\eta_f}\left(\pi_f{}^{\frac{\gamma_c - 1}{\gamma_c}} \quad 1\right)\right]$$

LPC

$$P_{o2} = P_{o9}\,\pi_{LPc}$$

$$T_{o2} = T_{o9}\left[1 + \frac{1}{\eta_{LPC}}\left(\pi_{LPC}{}^{\frac{\gamma_c - 1}{\gamma_c}} \quad 1\right)\right]$$

HPC

$$P_{o3} = P_{o2}\,\pi_{HPc}$$

$$T_{o3} = T_{o2}\left[1 + \frac{1}{\eta_{HPC}}\left(\pi_{HPC}{}^{\frac{\gamma_c - 1}{\gamma_c}} \quad 1\right)\right]$$

The Bleed station(7th from HPC)

$$\Delta T_{os} = \frac{T_{o3} \quad T_{o2}}{\text{No. of stages of HPC}}$$

$$T_{ob} = T_{o2} + (7 \quad \Delta T_{os})$$

$$P_{ob} = P_{o2} \quad \left(\frac{T_{ob}}{T_{o2}}\right)^{\frac{\gamma c \eta p}{\gamma c - 1}}$$

Assume equal work per stage of HPC.

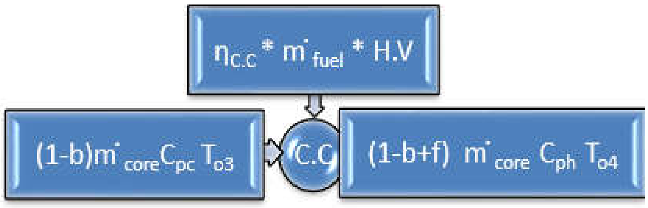
Taking η_p=0.92

Combustion Chamber

Assume T_{o4} (TIT)

$$P_{o4} = P_{o3}(1 \quad \Delta P_{c.c}\%)$$

From Energy Balance in the Combustion Chamber:-



$$(1 \quad b)m_{core}C_{pc}T_{o3} + \eta_{\mathrm{C.C}}m_{fuel}\,H.V = (1 \quad b + f)m_{core}C_{ph}T_{o4}$$

$$f = \frac{(1 \quad b)(C_{pc}T_{o3} \quad C_{ph}T_{o4})}{(C_{ph}T_{o4} \quad \eta_{\mathrm{C.C}}H.V.)}$$

From Energy Balance between HPT andLPC

$$\zeta\, m_{\mathrm{core}}\,\mathrm{C_{ph}}\eta_{\mathrm{mech}}(T_{\mathrm{o4}} \quad T_{\mathrm{o5}})(1 + f \quad b) = m_{\mathrm{core}}\,\mathrm{C_{pc}}(T_{\mathrm{ob}} \quad T_{\mathrm{o2}}) + m_{\mathrm{core}}(1 \quad b)\,\mathrm{C_{pc}}(T_{\mathrm{o3}} \quad T_{\mathrm{ob}})$$

$$T_{\mathrm{o5}} = T_{\mathrm{o4}} \quad \frac{\mathrm{C_{pc}}(T_{\mathrm{ob}} \quad T_{\mathrm{o2}}) + (1 \quad b)\,\mathrm{C_{pc}}(T_{\mathrm{o3}} \quad T_{\mathrm{ob}})}{\zeta\,\mathrm{C_{ph}}\eta_{\mathrm{mech}}(1 + f \quad b)}$$

$$P_{\mathrm{o5}} = P_{\mathrm{o4}}\left[1 \quad \frac{1}{\eta_{\mathrm{HPT}}}\left(1 \quad \frac{T_{\mathrm{o5}}}{T_{\mathrm{o4}}}\right)\right]^{\frac{\gamma_h}{\gamma_h - 1}}$$

$$\zeta = 0.85$$

Energy balance between LPT and Fan + LPC (Low pressure spool)

$$m_{\mathrm{core}}\,\mathrm{C_{ph}}\,\eta_{\mathrm{mech}}(T_{\mathrm{o5}} \quad T_{\mathrm{o6}})(1 + f \quad b) =$$
$$m_{\mathrm{core}}(1 + \beta)\,\mathrm{C_{pc}}(T_{\mathrm{o9}} \quad T_{\mathrm{o1}}) + m_{\mathrm{core}}\mathrm{C_{pc}}(T_{\mathrm{o2}} \quad T_{\mathrm{o9}})$$

$$T_{\mathrm{o6}} = T_{\mathrm{o5}} \quad \frac{(1 + \beta)\mathrm{C_{pc}}(T_{\mathrm{o9}} \quad T_{\mathrm{o1}}) + \mathrm{C_{pc}}(T_{\mathrm{o2}} \quad T_{\mathrm{o9}})}{\eta_{\mathrm{mech}}\mathrm{C_{ph}}(1 + f \quad b)}$$

$$P_{\mathrm{o6}} = P_{\mathrm{o5}}\left[1 \quad \frac{1}{\eta_{\mathrm{HPT}}}\left(1 \quad \frac{T_{\mathrm{o6}}}{T_{\mathrm{o5}}}\right)\right]^{\frac{\gamma_h}{\gamma_h - 1}}$$

Assume there aren't any pressure losses in the Jet pipe

$$T_{\mathrm{o7}} = T_{\mathrm{o6}}$$
$$P_{\mathrm{o7}} = P_{\mathrm{o6}}$$

Calculation P_{cf} (Critical Pressure in fan nozzle)

$$P_{\mathrm{cf}} = P_{\mathrm{o9}}\left[1 \quad \left(\frac{1}{\eta_{\mathrm{fn}}} \quad \frac{\gamma_c \quad 1}{\gamma_c + 1}\right)\right]^{\frac{\gamma_c}{\gamma_c - 1}}$$

$$P_{\mathrm{o11}} = P_{\mathrm{o9}}$$

- If $P_{\mathrm{cf}} < P_{\mathrm{a}}$ The fan nozzle isn't chocked

$$\therefore P_{11} = P_{\mathrm{a}}$$

$$V_{\mathrm{efan}} = \sqrt{2\,\mathrm{C_{pc}}\,\eta_{\mathrm{fn}}\,T_{\mathrm{o9}}\left(1 \quad \left(\frac{P_{\mathrm{a}}}{P_{\mathrm{o9}}}\right)^{\frac{\gamma_c - 1}{\gamma_c}}\right)}$$

$$T_{09} = T_{011}$$

$$T_{11} = T_{\mathrm{o11}} \quad \frac{{V_{\mathrm{efan}}}^2}{2\mathrm{C_{pc}}}$$

Mach number at fan nozzle exit (M_{ef})

$$M_{\mathrm{ef}} = \frac{V_{\mathrm{efan}}}{\sqrt{\gamma_c R_c T_{11}}}$$

- If $P_{\mathrm{cf}} \geq P_{\mathrm{a}}$ ⇒⇒ The nozzle is Chocked
-

$$\therefore P_{11} = P_{\mathrm{cf}}$$

$$T_{11} = \frac{2\,T_{o11}}{\gamma_c+1}$$

$$V_{efan} = \sqrt{\gamma_c R_c\, T_{11}} = \text{sonic speed}$$
Where $R_c = 287$ J/Kg.K

Check for chocking in Turbine nozzle

Calculation P_{ct} (Critical Pressure in turbine nozzle)

$$P_{cf} = P_{o7}\left[1 \quad \left(\frac{1}{\eta_{tn}} \quad \frac{\gamma_h \quad 1}{\gamma_h + 1}\right)\right]^{\frac{\gamma_h}{\gamma_h - 1}}$$

$$P_{o7} = P_{o8}$$

- If $P_{ct} < P_a$ The nozzle isn't chocked

$$\therefore P_8 = P_a$$

$$V_{eturbine} = \sqrt{2\,C_{ph}\,\eta_{tn}\,T_{o7}\left(1 \quad \left(\frac{P_a}{P_{o6}}\right)^{\frac{\gamma_h - 1}{\gamma_h}}\right)}$$

$$T_{o7} = T_{o8}$$

$$T_8 = T_{o8} \quad \frac{V_{e\,turbine}^{\;2}}{2C_{ph}}$$

Mach number at turbine nozzle exit (M_{et})

$$M_{et} = \frac{V_{eturbine}}{\sqrt{\gamma_h R_h T_8}}$$

- If $P_{ct} \geq P_a$ ⇒⇒ The turbine nozzle is Chocked

$$\therefore P_8 = P_{ct}$$

$$T_8 = \frac{2 \quad T_{o8}}{\gamma_h + 1}$$

$$V_{eturbine} = \sqrt{\gamma_h R_h\, T_8}$$ Where $R_h = 284.84$ J/Kg.K

i. specific Thrust force calculation:

$$\frac{T\ rust}{m_{total}} = \left(\frac{1+f}{1+\beta}\right)V_{eturbine} + \left(\frac{B}{B+1}\right)V_{efan} + \left(\frac{1+f}{1+\beta}\right)\frac{R_h T_8}{P_8\, V_{eturbine}}(P_8 \quad P_a) + \left(\frac{B}{B+1}\right)\frac{R_c T_{11}}{P_{11} V_{efan}}(P_{11} \quad P_a)$$

$$V_{flight}$$

ii. Thrust Specific Fuel Consumption

$$TSFC = \frac{m_{fuel}}{T\ rust}$$

$$TSFC = \frac{f}{(1+B) \quad \left(\frac{Thrust}{m_{total}}\right)}$$

iii. Propulsive Efficiency Calculation

$$p = \frac{\left(\frac{T}{m_{total}}\right) V_{flight}}{\left(\frac{T}{m_{total}}\right) V_{flight} + 0.5\left(\frac{1+f}{1+\beta}\right)(V_{eturbine} \quad V_{flight})^2 + 0.5\left(\frac{\beta}{1+\beta}\right)\left(V_{efan} \quad V_{flight}\right)^2}$$

Where:

$\boldsymbol{V}_{\mathbf{flight}}$ =flight speed
$\boldsymbol{V}_{\mathbf{eturbine}}$=turbine exhaust velocity
V_{efan}=fan exhaust velocity
β=Bypass ratio
f=Fuel to air ratio
$\frac{T}{m_a}$=specific thrust (KN.s/Kg)
m_a=total mass flow rate $=m_{core}+m_{fan}$

iv. Thermal Efficiency Calculation

$$_{th} = \frac{\left(\frac{T}{m_{total}}\right)V_{flight} + 0.5\left(\frac{1+f}{1+\beta}\right)\left(V_{eturbine}\quad V_{flight}\right)^2 + 0.5\left(\frac{\beta}{1+\beta}\right)\left(V_{efan}\quad V_{flight}\right)^2}{\left(\frac{f}{1+\beta}\right)H.V\quad_{c.c}}$$

v. Overall Efficiency Calculation

$$-\ _{o} = \ _{p}\ \ _{th}$$

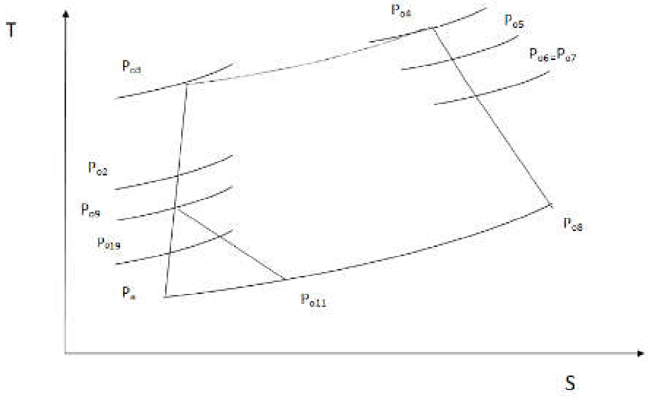


Fig. 11: T-s diagram for two spool turbofan engine(Unmixed flow type)

Table 2: Assumed Engine Modules Efficiencies

Intake	Fan	LPC	HPC	LPT	HPT	C.C	η_{mech}	Fan nozzle	Turbine nozzle
0.97	0.91	0.91	0.91	0.92	0.92	0.99	0.99	0.96	0.96

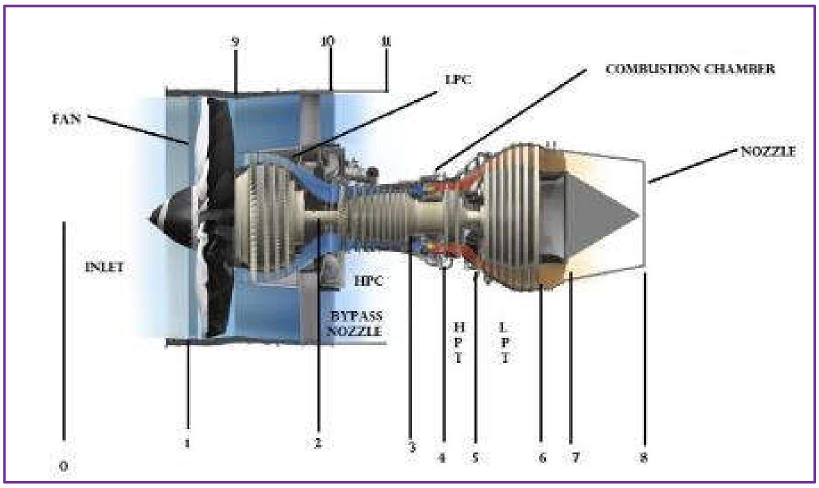
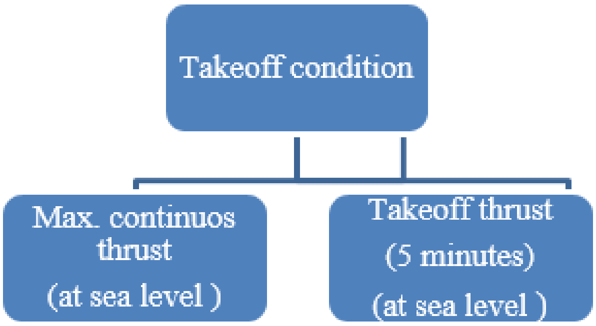


Fig. 12. GEnx-1B70 modules and Stations numbering

Takeoff condition



Max. Continuos Thrust (At Sea Level)Analysis Results

Height (km)	0.0
Mach No.	0.0
Ca (m/s)	0.0
π_{Ram}	1.0
π_{fan}	1.4
π_{LPC}	1.3
π_{HPC}	23.9
TIT(K°)	1690
ma (kg/s)	1155.43
mf (kg/s)	2.82
Thrust force (KN)	293.25
Sp. Thrust (KN-s/kg)	0.25
TSFC(Kg/S.KN)	0.01
Hot Jet velocity(m/s)	389.14 The Turbine Nozzle is not chocked
cold jet velocity (m/s)	237.88 The Fan Nozzle is not chocked

The pressure and temperature at each station
(Max. Continuos Thrust (At Sea Level))

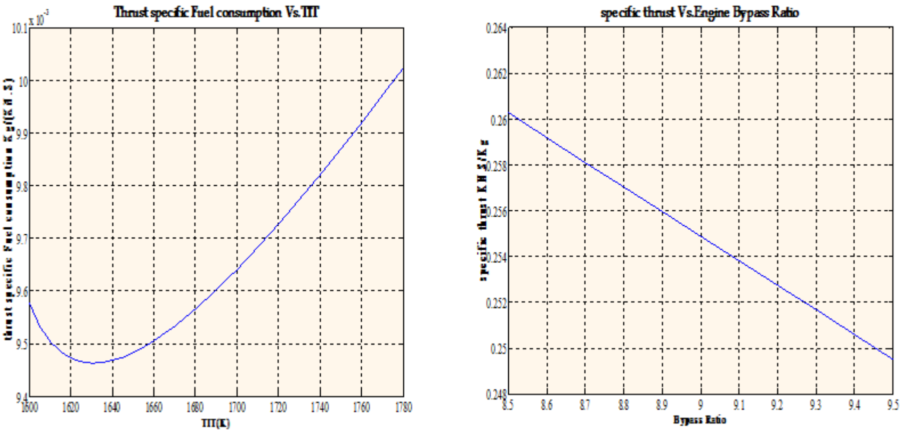
Station No.	Total Temperature(K)	Total Pressure(Kpa)
1	288.00	101.325
2	347.30	184.4115
Bleed station	741.75	2122.99
3	910.80	4407.6375
4	1690.00	4319.48475
5	1104.16	642.29973
6	791.85	146.12272
7	791.85	146.12272
8	791.85	146.12272
9	319.94	141.855
10	319.94	141.855
11	319.94	141.855

Takeoff Thrust (5 Minutes)(At Sea Level) Analysis Results

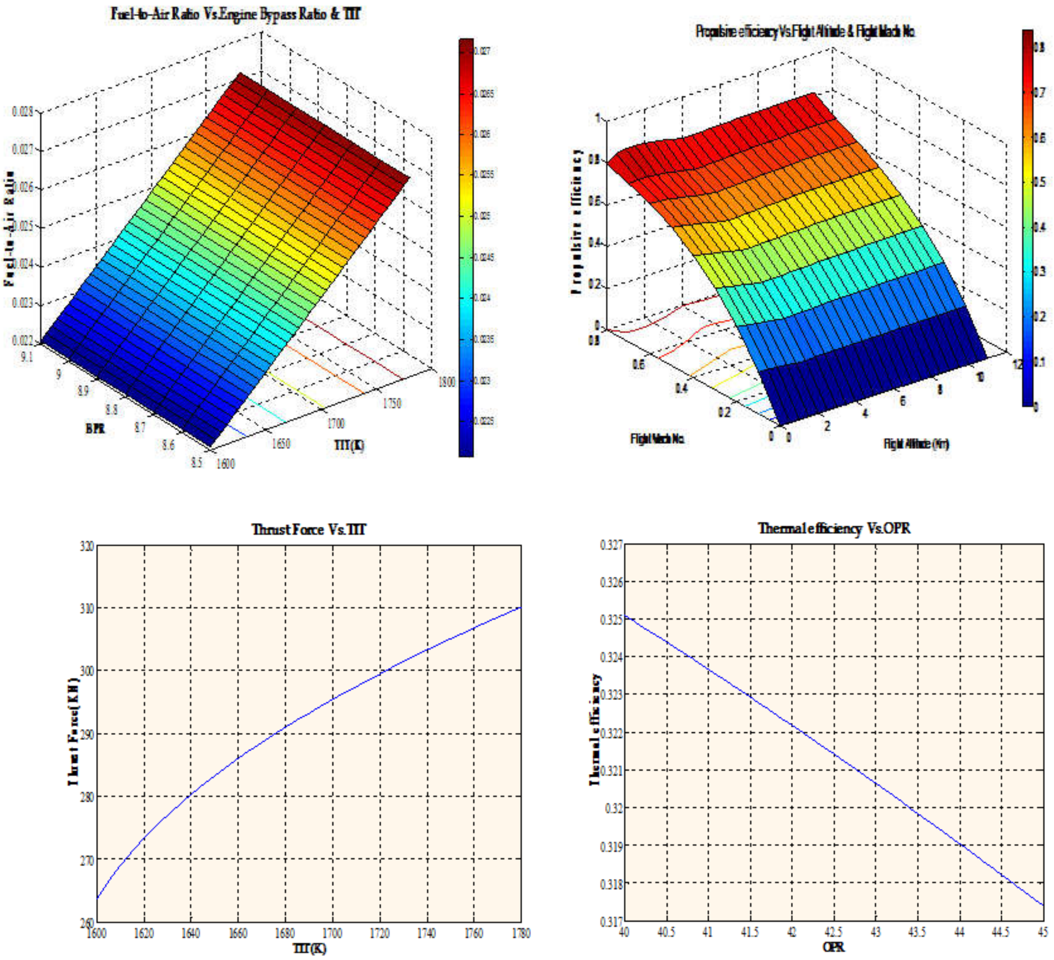
Height (km)	0.0
Mach No.	0.0
Ca (m/s)	0.0
π_{Ram}	1.0
π_{fan}	1.5
π_{LPC}	1.3
π_{HPC}	22.3
TIT(K°)	1790
ma (kg/s)	1155.43
mf (kg/s)	3.21
Thrust force (KN)	320.48
Sp. Thrust (KN-s/kg)	0.28
TSFC(Kg/S.KN)	0.01
Hot Jet velocity(m/s)	401.92 The Turbine Nozzle is not chocked
cold jet velocity (m/s)	262.67 The Fan Nozzle is not chocked

The pressure and temperature at each station (Takeoff Thrust (5 Minutes) (At Sea Level))

Station No.	Total Temperature(K)	Total Pressure(Kpa)
1	Ta=288.00	Pa =101.325
2	354.83	197.58375
Bleed station	744.64	2149.58
3	911.70	4407.63750
4	1790.00	4319.48475
5	1212.70	758.41206
6	838.39	146.05499
7	838.39	146.05499
8	838.39	146.05499
9	326.87	151.98750
10	326.87	151.98750
11	326.87	151.98750



2-D Performance Analysis (Takeoff)

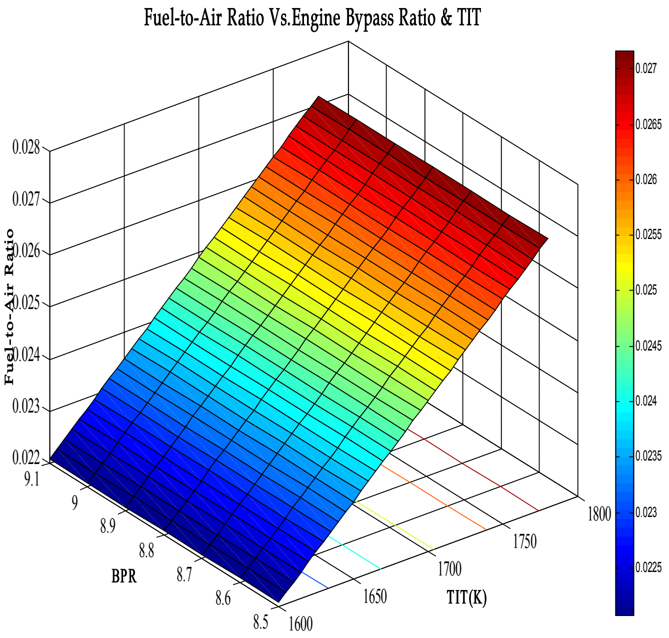


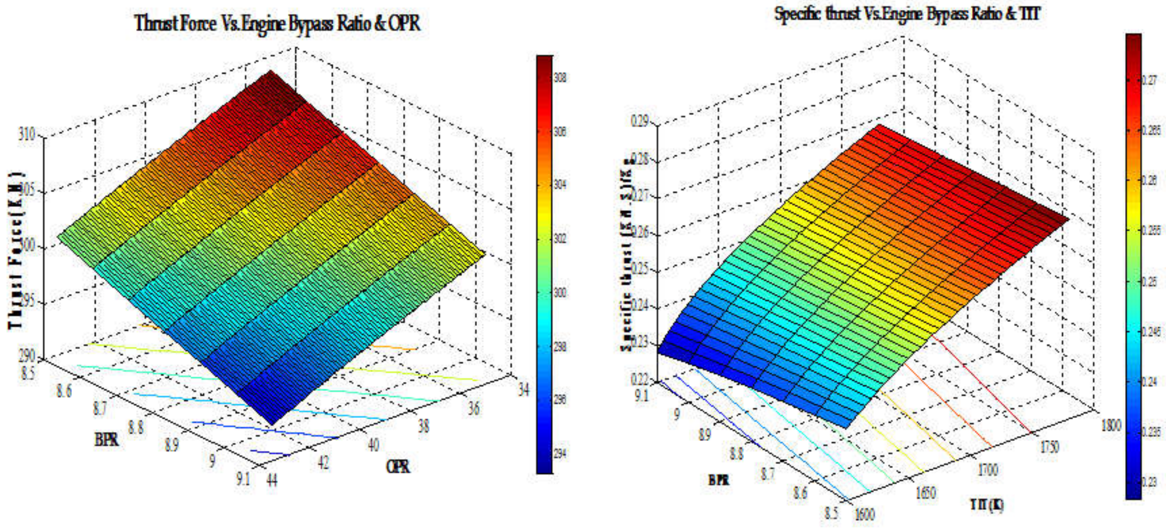
3-D Performance Analysis (Takeoff)

Cruise condition

Analysis Results

Height (km)	10.668
Mach No.	0.85
Ca (m/s)	251.95
π_{Ram}	1.58
π_{fan}	1.5
π_{LPC}	1.3
π_{HPC}	22.3
TIT(K^o)	1470
ma (kg/s)	597.88
mf (kg/s)	1.184
Thrust force (KN)	60.64
Sp. Thrust (KN-s/kg)	0.10
TSFC(Kg/S.KN)	0.02
Hot Jet velocity(m/s)	395.58 The Turbine Nozzle is not chocked
Cold Jet Velocity (m/s)	308.39 The Fan Nozzle is chocked

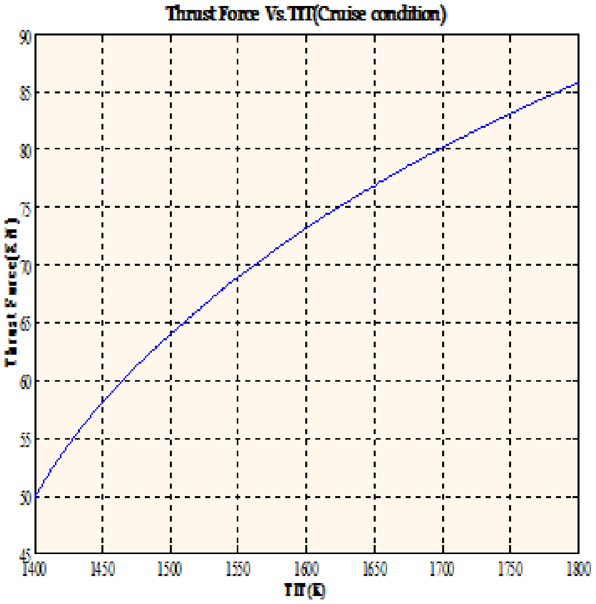


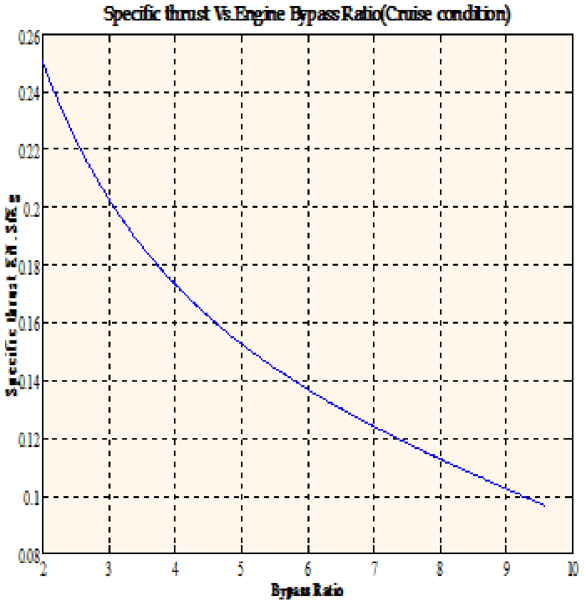


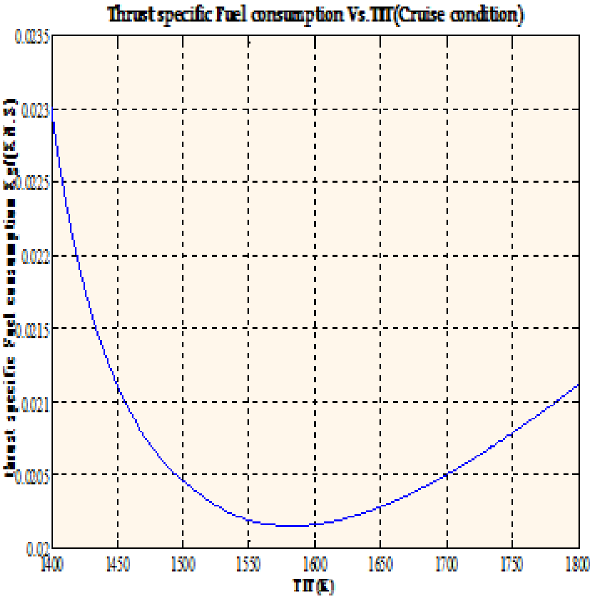
2-D Performance Analysis (Cruise Condition)

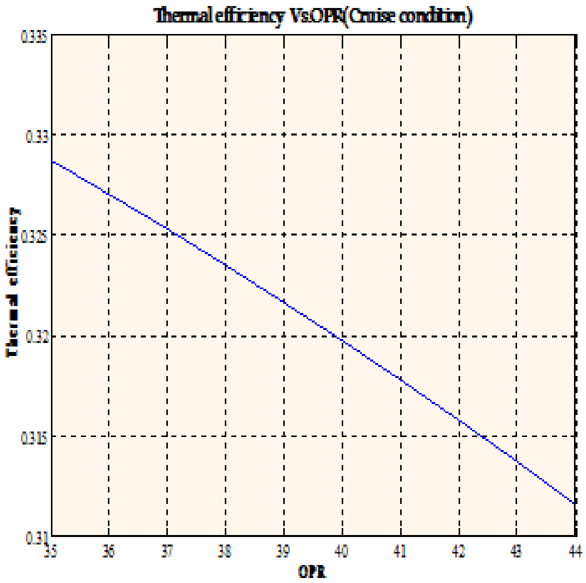
The pressure and temperature at each station (Cruise condition)

Station No.	Total Temperature(K)	Total Pressure(Kpa)
1(static)	Ta=218.66	Pa =23.81046
2	308.33	73.48344
Bleed station	647.05	799.43
3	792.21	1639.24587
4	1470.00	1606.46095
5	965.24	244.42068
6	637.96	38.32276
7	637.96	38.32276
8	637.96	38.32276
9	284.03	56.52572
10	284.03	56.52572
11	284.03	56.52572

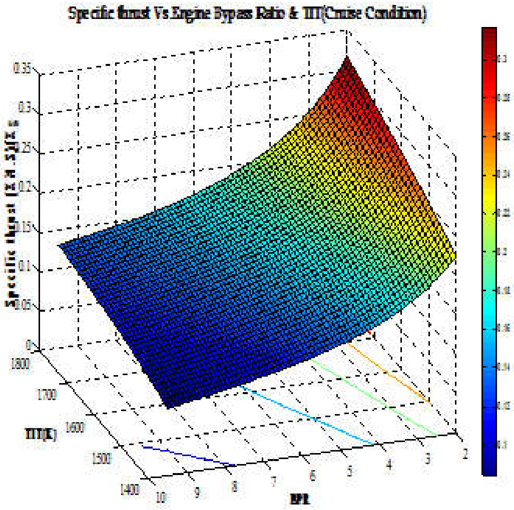


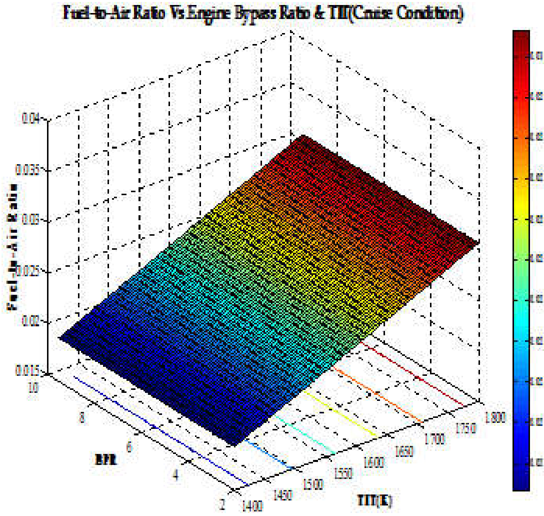


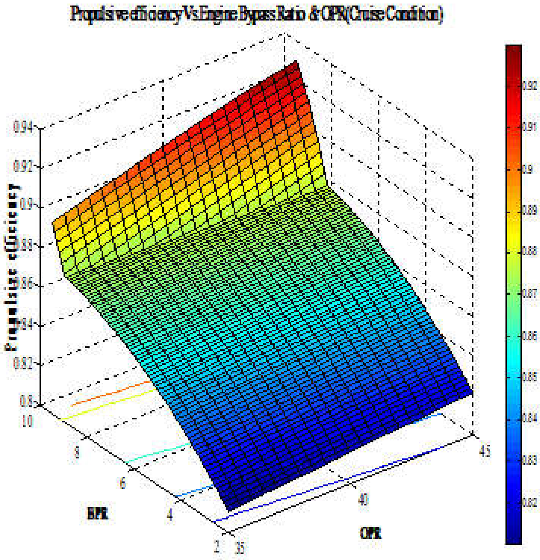


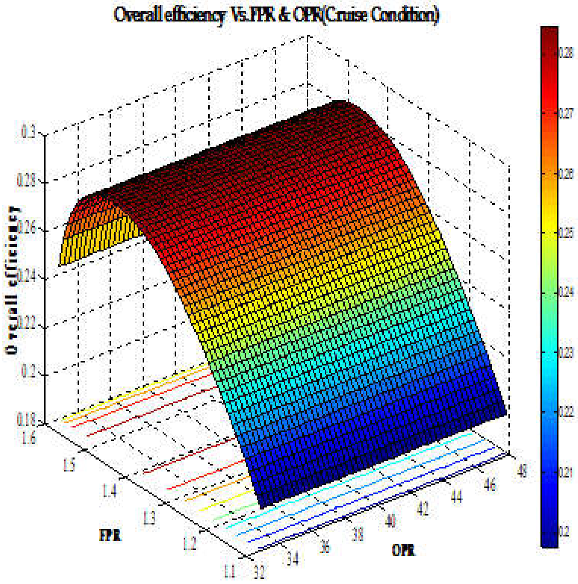


3-D Performance Analysis (Cruise Condition)


Specific thrust Vs Engine Bypass Ratio & TIT(Cruise Condition)


Fuel-to-Air Ratio Vs Engine Bypass Ratio & TIT(Cruise Condition)


Propulsive efficiency Vs Engine Bypass Ratio & OPR(Cruise Condition)


Overall efficiency Vs FPR & OPR(Cruise Condition)

Conclusion

The turbofan engine has a high thrust capability with low fuel consumption. From our study to the performance of one model of the turbofan engine we concluded that thrust force increases when the turbine inlet temperature increases but there is a metallurgical limitation. The thermal efficiency decreases when the overall pressure ratio of the engine increases. The specific thrust decreases when the bypass ratio increases. Finally, as the turbofan engines have many advantages, they are used the modern age in transportation and military aircrafts.

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