PROPULSION - Gas Turbines

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October 2, 2016

Assignment 1

About the code:

- *The code for turbofan is formulated such that it considers to check if each of the nozzles choke or not. It is assumed that the mass flow rate will not change, thus letting the exit area flexible. Essentially, when choked, the code gives the desgin exit diameters for that particular choking condition.*
- *The code for turbojet with afterburner uses a variable* ***afterburner*** *which must be set to 1 or 0 depending on whether the afterburner is enabled or not (respectively.) Even here, the calcutions consider a constant undisturbed mass flow rate and gives the design exit nozzle diameter when choked. The reaction of the engine after the choking point has not been taken into account,i.e, decrease in mass flow rate for a fixed nozzle design is not considered.*
- *The PDFs of code runs have been linked wherever necessary.*

1 Turbofan Engine.

Parameter	Magnitude
T_∞	220 K
P_∞	0.25 atm
M_∞	0.85
π_{fan}	1.72
η_{diff}	0.93
η_{comp}	0.85
$(\eta_n)_{cold}$	0.98
$(\eta_n)_{hot}$	0.98
η_{burner}	1
$(\triangle p_o)_{burner}$	0
JP4 Q	45 MJ

Table 1: Engine data

Before comparing the specific thrust and the TSFC for the turbine inlet temperature T_{04} in the range 1630 K to 1730 K, it is necessary to determine whether the cold stream and hot stream nozzles choke or not. If the nozzles choke, there is no longer complete expansion to the atmosphere. Thus, the thrust includes both the momentum as well as pressure thrusts. It's necessary to determine the range of B, π_C, T_{04} in which the nozzles choke. Further, there are four different combinations of the nozzles choking.(Hot stream nozzle and cold stream nozzle). For the given fan pressure ratio, the fan nozzle chokes as the pressure ratio at the fan nozzle is below the critical pressure ratio given by,

$$\frac{p_c}{p_{08}} = [1 - \frac{1}{\eta_{n_{cold}}}(\frac{\gamma - 1}{\gamma + 1})]^{\frac{\gamma}{\gamma - 1}} \tag{1}$$

Similarly, the choking of the core hot nozzle can be discussed based on the critical pressure ratio determined by a similar formula as (1). P_{06} is the determining pressure for choking. It's variation with the TIT (Turbine Inlet Temperature T_{04}) and B is given in figures (1) & (2).

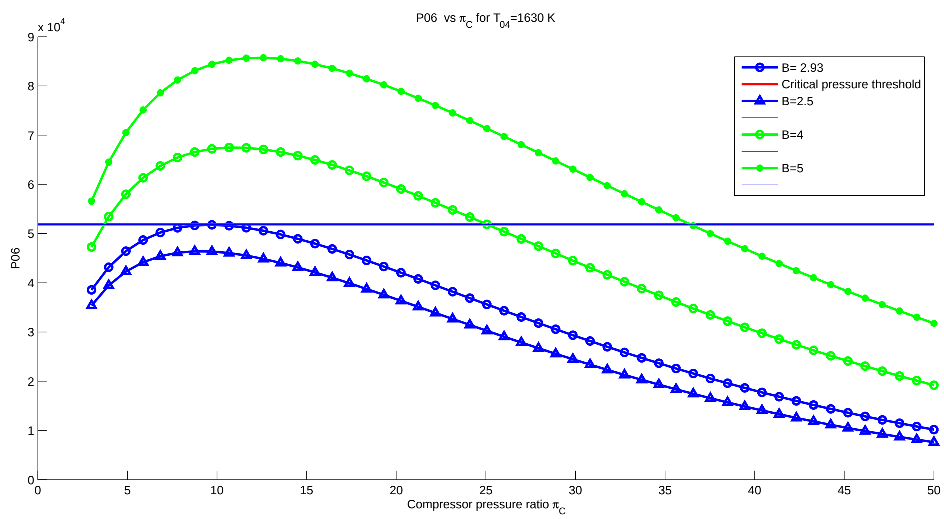

Figure 1: Variation of P_{06} for fixed TIT for various B

Figure (1) shows a critical pressure line. If P_{06} goes above the line, the core nozzle chokes. As can be seen from the graph, choking starts for B=2.93.

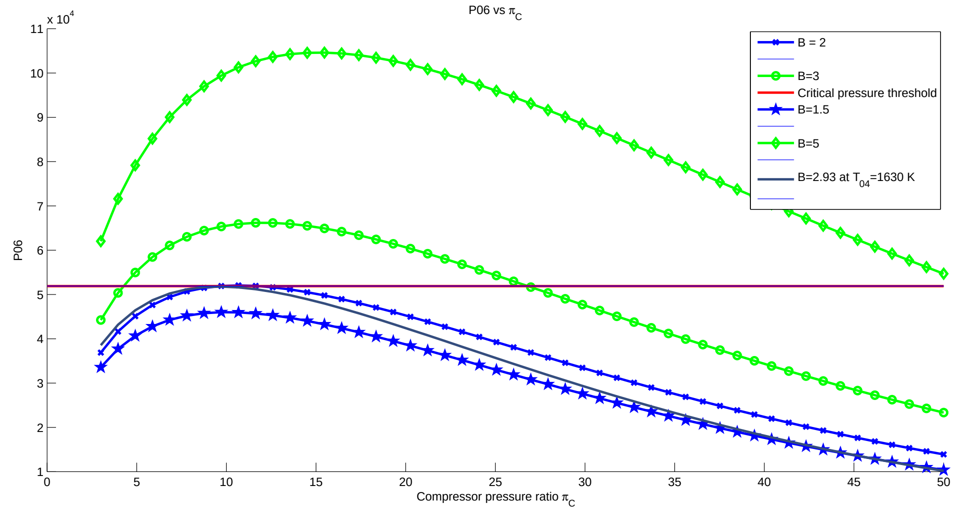

Figure 2: Variation of P_{06} for fixed TIT=1730 for various B

From figure (2) it can be seen that the curves shift to right as the TIT is increased from 1630K tp 1730K. Also the range of pressure ratios in which the nozzle chokes increases with B and TIT.

The Matlab code runs for the curves where it just touches the critical threshold is below. These are the points where the nozzle starts to choke for the first time.

- TIT=1630 K, B=2.93

https://drive.google.com/file/d/0B0snWZIsu8Gqb2Y4Nk90SEhJems/view?usp=sharing

- TIT=1730, B=2

https://drive.google.com/file/d/0B0snWZIsu8GqdVBxYXlfVExuY1U/view?usp=sharing

It can be seen that for a higher TIT, the nozzle chokes at much lower pressure ratio of the compressor. So for bypass ratios greater than these, the core nozzle chokes for a wide range of compressor pressure ratio.

For the given range of pressure ratio and B=5-10, both the nozzles are choked for most of the TIT in the range 1630K to 1730K. The comparison of specific thrusts and TSFC below considers the choking of the nozzles.

1.1 Specific thrust

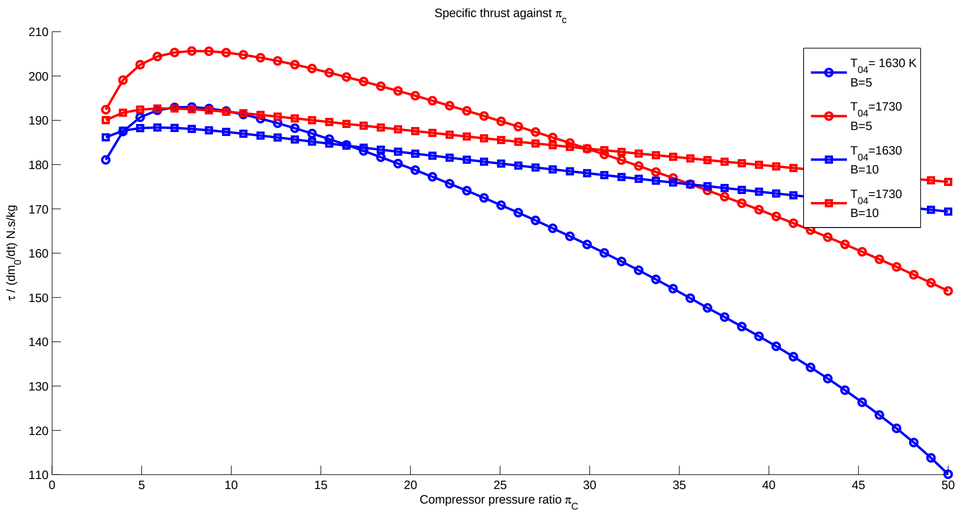

Figure 3: Variation of Specific thrust with TIT and B

Figure (3) shows the variation of specific thrust under different conditions. Keeping the bypass ratio constant, if the TIT is increased, the curve shifts upwards,i.e., specific thrust increases. Now if the TIT is kept constant and the bypass ratio is increased, the curve tends to flatten downwards. Thus there's a small range of pressure ratios where the specific thrust is higer for lower bypass and the vice versa beyond. This 'range' of pressure ratio widens for higher TIT. **Essentially, higer specific thrust can be obtained more effectively by increasing TIT rather than increasing B.** [*The reason that there exists a range where the properties change is that, as bypass ratio increases the nozzle is about to choke, nay, the range corresponds to the range of choking seen in fig (1) and (2)*]

1.2 TSFC

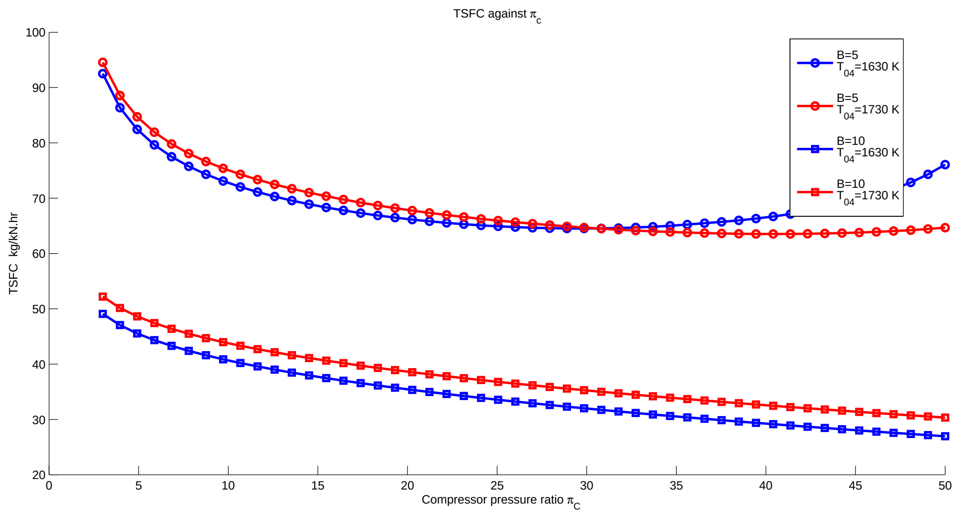

Figure 4: Variation of TSFC with TIT and B

Figure (4) shows the variation of TSFC with TIT and B. For a given B, if the TIT is increased, the curve shifts downward. Thus the thrust specific fuel consumption reduces for higher bypass ratios. Now if the bypass ratio is fixed and TIT increased, there's a range of pressure ratio where the TSFC is higher for higer TIT. This 'range' widens with increase in B. For B=10, TSFC is evidently higher for higher TIT for the entire pressure range. **Thus, to reduce fuel consumption it is better to increase B than reducing TIT.**

1.3 Efficiencies

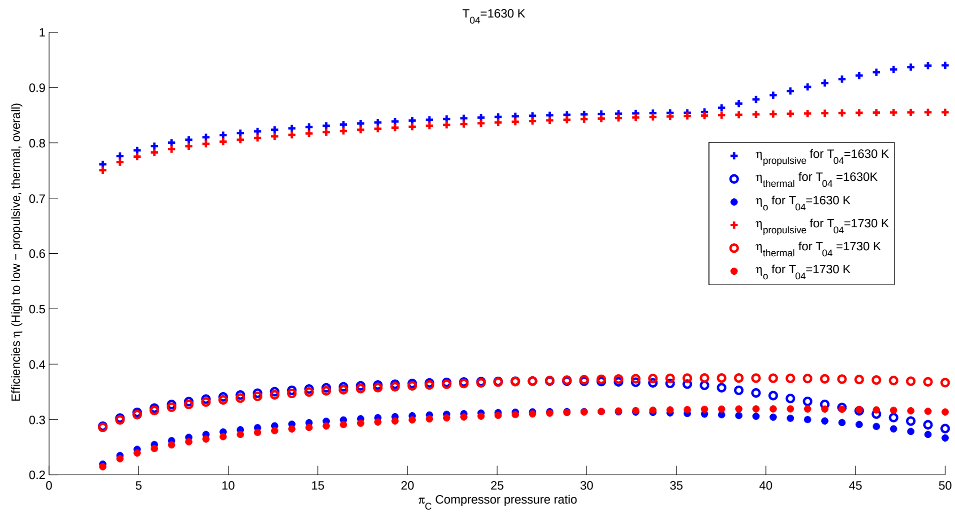

Figure 5: Variation of efficiencies for B=5

Figure shows (5) variation of efficiencies with TIT. ***Propulsive efficiency*** > ***Thermal efficiency*** > ***Overall efficiency***. Propulsive efficiency is higher for lower TIT in **most of the range.** The trends are same for thermal and overall efficiencies. If B=10, the trend holds for a wider range of pressure ratios. That is, efficiencies decrease for increase in TIT.

If the TIT is kept constant and B is increased, the efficiencies increase. The increase in thermal efficiency is significant, thus increasing the overall efficiency. (Since, these are plot for TIT=1730 K, the nozzles choke in the entire range, which is why the curves don't cross.) **Thus, higher efficiency can be obtained by increasing TIT rather than B.**

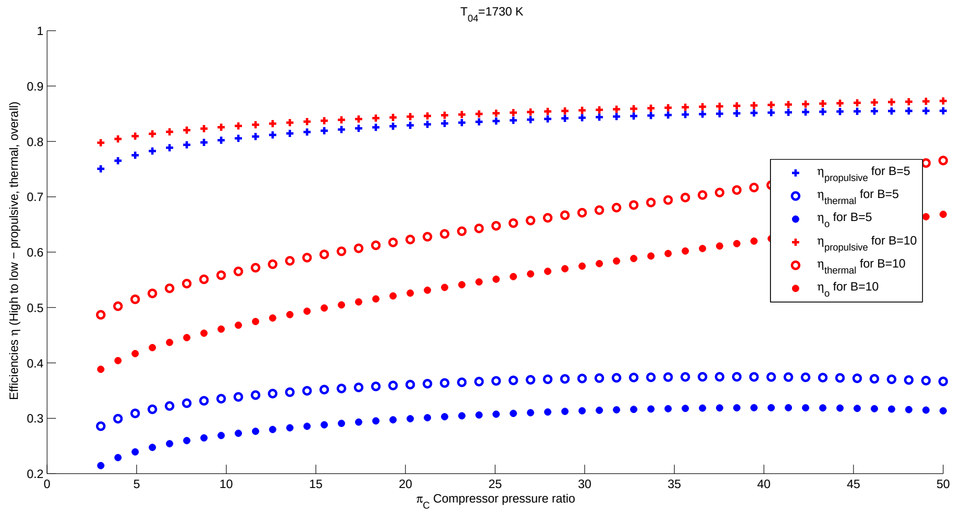

Figure 6: Variation of efficiencies for TIT=1730K

1.4 TSFC vs Specific thrust

The variation of TSFC with specific thrust is given in the figure (7).

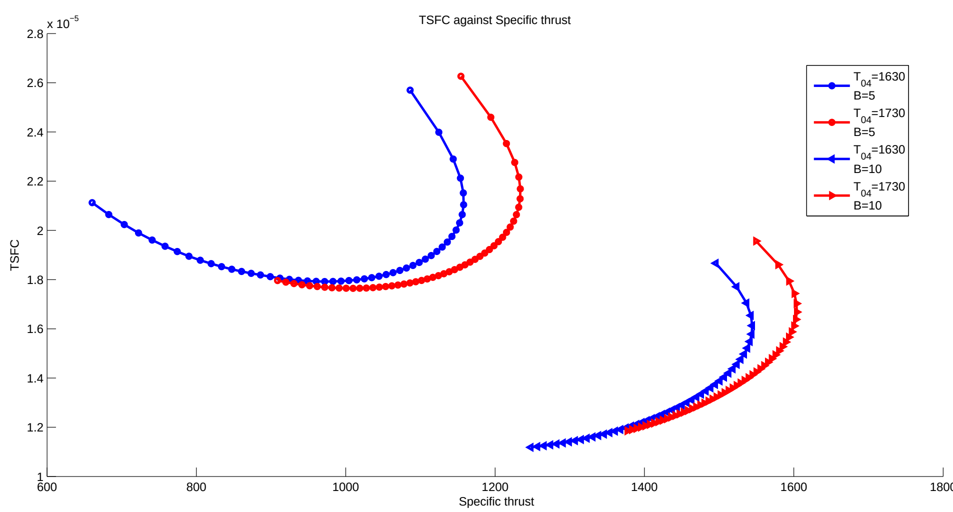

Figure 7: Variation of TSFC with Specific thrust with TIT and B

For a given TIT, if B is increased, the TSFC reduces. For a fixed B, if the

TIT is creased TSFC reduces. Evidently, the reduction is higher if the bypass ratio is increased rather than increasing TIT. **Thus, it is better to increase B to reduce fuel consumption than decrease TIT.**

2 Turbojet with afterburner.

Station	Temperature	Pressure
∞	$T_\infty = 220$K,$T_{0\infty} = 251.79$K	$P_\infty = 25331.25Pa$, $P_{0\infty} = 40626.73Pa$
$1 = 2$(no losses)	$T_{02} = 251.79$K	$P_{02} = 40091Pa$
3	$T_{03} = 480.28$K	$P_{03} = 288650Pa$
4	$T_{04} = 1130$K	$P_{04} = 288650Pa$
5	$T_{05} = 899.20$K	$P_{05} = 112450Pa$
6	$T_{06} = 899.20$K	$P_{06} = 124500Pa$
6A (with afterburner)	$T_{06A} = 1200$K	$P_{06A} = 124500Pa$
7 (no afterburner)	$T_7 = 1000$K, $T_{07} = 1200$K	$P_7 = 58561Pa$ $P_{07} = 188238$Pa
7 (with afterburner)	$T_7 = 749.34$K, $T_{07} = 899.20$K	$P_7 = 58561Pa$ $P_{07} = 188238$Pa

Table 2: ***RD 9 pressures and temperatures for*** $\pi_C = 7.2$

The variation of specific thrust **t** with compressor pressure ratio is given by the figures (8) & (9). (Both the cases where afterburner is disabled and enabled respectively)

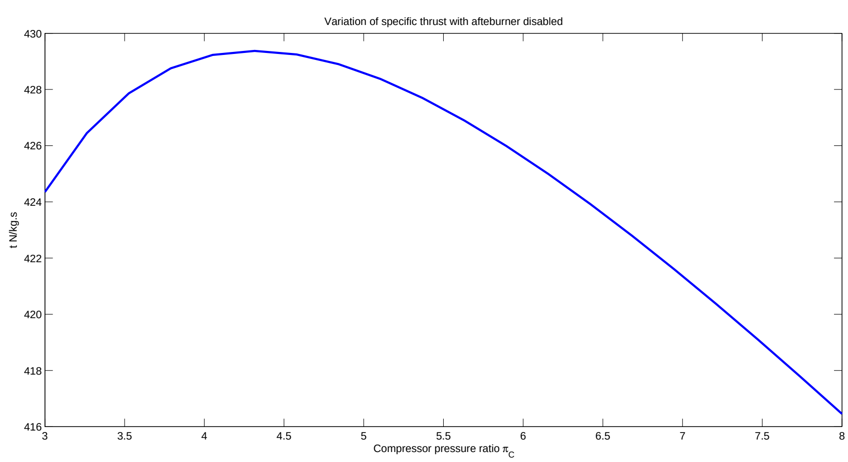

Figure 8: Variation of specific thrust with afterburner disabled. The maximum **t** is obatained for $\pi_c = 4.4$

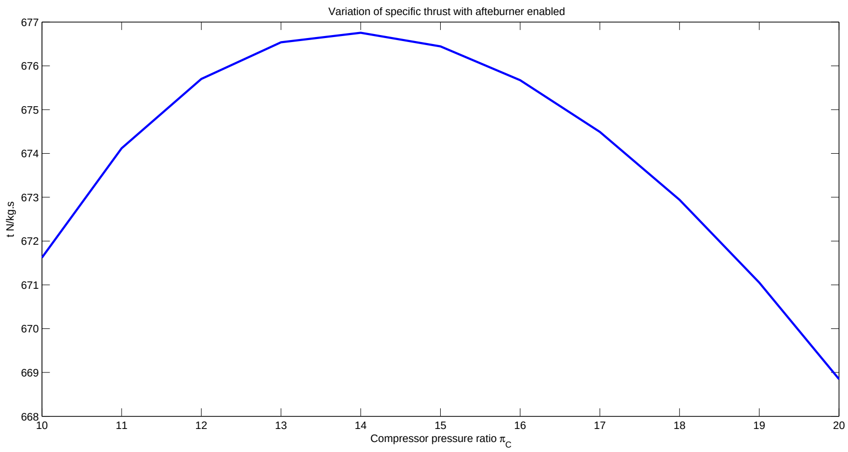

Figure 9: Variation of specific thrust with afterburner enabled. The maximum **t** is obatained for $\pi_c = 14$.

Afterburner	**disabled**	**disabled**	**enabled**	**enabled**
π_c	4.4 (for max **t**)	7.2	14 (for max **t**)	7.2
Nozzle choking	Yes	Yes	Yes	Yes
f	**0.0174**	**0.0157**	**0.013**	**0.0157**
f_{ab}	0	0	0.0197	0.0144
v_7	569.75 m/s	548.71 m/s	633.88 m/s	633.88 m/s
Specific thrust **t**	429.36 N/kg.s	420.42 N/kg.S	676.78 N/kg.s	657.15 N/kg.s
TSFC **s**	**158.56kg.hr/kN**	**134.29kg.hr/kN**	**174.12kg.hr/kN**	**164.86kg.hr/kN**
diameter	0.5141m	0.4617 m	0.6553 m	0.6876 m
$\eta_{propulsive}$	0.6797	0.7048	0.6951	0.6894
$\eta_{thermal}$	0.2043	0.2136	0.1670	0.1779
$\eta_{overall}$	0.1389	0.1505	0.1161	0.1226
Net thrust	20.61 kN	20.18 kN	32.48 kN	31.54 kN

Table 3: *Calculated Engine data for maximum specific thrust and the design point*

In order to obtain maximum specific thrust, the engine should be operated at $\pi_c = 4.4$ and $\pi_c = 14$ for the cases where afterburner is disabled and enabled respectively. But if the engine is run at $\pi_c = 7.2$, the specific fuel consumption is significantly lower, but there is not a significant change in the thrust obtained. Similarly, the augumented thrust also doesn't change much for maximum specific thrust case and design $\pi_c = 7.2$. **Thus, $\pi_c = 7.2$ is an optimal design trade-off to reduce fuel consumption without losing much of thrust. Moreover, it can be seen that the efficiencies are higer for $\pi_c = 7.2$**

rather than at maximum specific thrust.

The Matlab code runs for the four cases can be found in the links below.

1. Afterburner disabled for maximum specific thrust - https://drive.google.com/file/d/0B0snWZIsu8GqTkNIVndVeXo5Qlk/view?usp=sharing
2. Afterburner enabled for maximum specific thrust - https://drive.google.com/file/d/0B0snWZIsu8GqMkVXMW1SdFlMVGs/view?usp=sharing
3. Afterburner disabled for $\pi_C = 7.2$ - https://drive.google.com/file/d/0B0snWZIsu8Gqb2Y4Nk90SEhJems/view?usp=sharing
4. Afterburner enabled for $\pi_C = 7.2$ - https://drive.google.com/file/d/0B0snWZIsu8GqVXBqUVJkcHBUMWs/view?usp=sharing

3 Bonus

3.1 [a]

3.1.1 Turbine blades & Compressor blades.

Turbine inlet temperature is one of the prime design parameters for developing a new engine. With development of improved material properties to withstand high centrifugal and thermal stresses over the years, the engine efficiencies have increased and higher thrusts have been achieved. Over the years, new methods like cooling of blades have been employed to obtain better operating points.

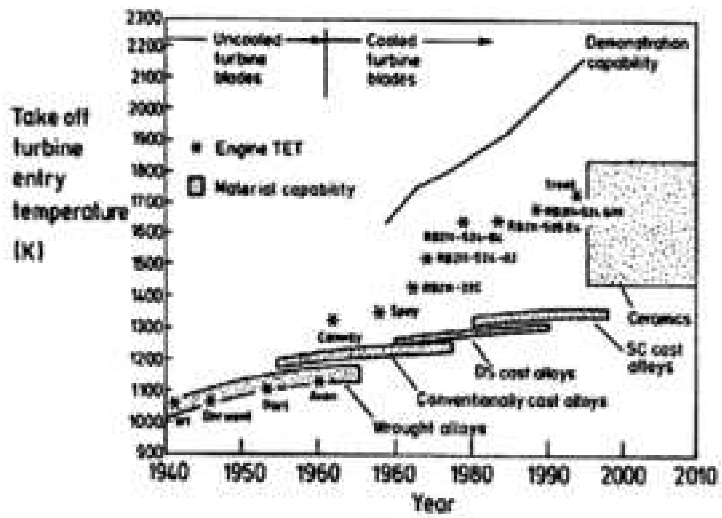

Figure 10: *Turbine inlet temperature Vs Year of manufacture. Source [3] Gas turbine manufacturing companies intending to develop a new engine interpolate this graph to estimate the max TIT by the time they would have completed their engine design. This is only a rough ball-park estimate. Source [4], [6]*

- The primary material of interest in compressors or turbines is Titanium, because of its high strentgh to weight ratio. It has been in use since 1950's and its coposition has increased from 3% to 33%. *Source[5]*

- Modern turbine blades often use nickel-based super alloys that incorporate chromium, cobalt and rhenium.

- **Ceramic matrix composites (CMC).** The main advantage of CMC materials over conventional super alloys is their light weight and high temperature capability. One such composite is SiC/SiC composite consisting of silicon matrix reinforced by silicon carbide fibers.

- Turbine and compressor discs employ Nickel-base, Steel-base, Aluminum-base superalloys. *Source[5]*

- Single crystal blades have the advantage of high operating temperature and creep resistance to a large TIT). Their manufacture is done by a process called **Autonomous Directional Solidification/ Directional Solidification.** The blades are usually known as DS blades in the manufacturers' lingo. Directional solidification techniques have been in development for over 60 years and Single crystal blades pioneered about 30 years ago demonstrate exceptional stress loading. *Source[4] Chapter 4, Source[7].*

- Some of the specific alloys used by GE and Rolls-Royce for turbine and compressor blades over the years are listed below. *Source[4] Chapter 4*

U-500	Nimonic 263
Rene 95	Nimonic 90
Rene N5, N6	Nimonic 80a
PWA1484	GTD-111
Inconel IN-738	CMSX-10

Compositons:

- Rene 95 - 66Ni14Cr8Co3.5Mo3.5W3.5Nb2.5Ti3.5Al 0.16C0.01B0.05Zr
- IN 718 - 60Ni19Cr18.5Fe3Mo0.9Ti0.5Al5.1Cb 0.03C

3.1.2 Combustor

Even combustors mainly employ Nickel-base and Cobalt-base superalloys. Hastelloy X (alloy of Ni,Cr,Co,Fe,W,Mo,C,B) a material with higher creep strength was used from 1960s to 1980s.

3.2 [b]

My observation on running the code for multiple values of the fan pressure ratio π_{fan} in the range of 1-1.72 showed that the fan only chokes beyond π_{fan}~1.5. Choking of the cold stream implies that the useful momentum thrust is reduced and a lower pressure thrust kicks in. This is inefficient, and effectively implies lesser thrust. By using a stator, effectively, the fan stage pressure ratio increases and thus, the cold nozzle tends to choke. Thus, using a stator is inefficient. Best efficiency is obtained for intermediate values of the pressure ratio where the cold nozzle is not choked.

References

[1] Gas turbine theory - Cohen, Rogers, Saravanmuttoo

[2] Mechanics and Thermodynamics of Propulsion - Hill & Peterson

[3] http://web.mit.edu/16.unified/www/SPRING/propulsion/notes/node27.html

[4] https://drive.google.com/file/d/0B0snWZIsu8GqLWhJUlpxMENDX0E/view?usp=sharing HAL Engine Divsion Internship

[5] http://cdn.intechweb.org/pdfs/22905.pdf

[6] https://powergen.gepower.com/content/dam/gepower-pgdp/global/en_US/documents/technical/ger/ger-3569g-advanced-gas-turbine-materials-coatings.pdf

[7] http://cannonmuskegon.com/wp-content/uploads/2015/02/Directionally-Solidified-and-Single-Crystal-Superalloys.pdf