JET PROPULSION

Thrust equation for an air breathing engine:

$$F = \dot{m}_a\,[(1+f)\,C_j - C_a)] + (P_e - P_a)\,A_e$$

Where, f = fuel to air ratio,

Neglecting f,

$$F = \dot{m}_a\,(C_j - C_a) + (P_e - P_a)\,A_e$$

$\dot{m}_a$ (Cj - Ca) = momentum thrust

(Pe - Pa) Ae = pressure thrust

$\dot{m}_a$ = mass flow rate of air entering the engine

Cj = exit velocity

Ca = inlet velocity

Pe = exit pressure

Pa = ambient pressure

F = thrust

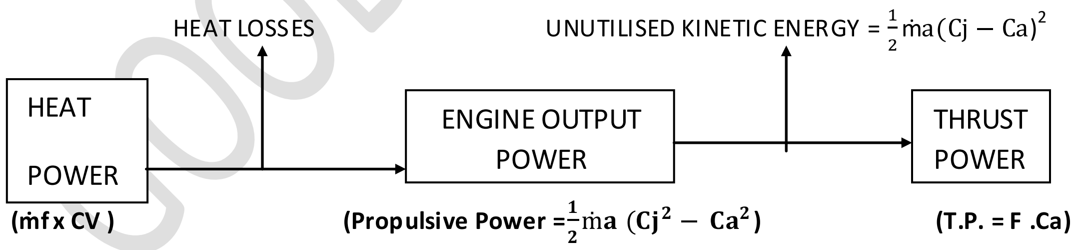
$\dot{m}_a$ Cj = gross momentum thrust

$\dot{m}_a$ Ca = intake drag

- For maximum thrust, expansion should optimum i.e. Pe =Pa

$$\therefore F = \dot{m}a\,(Cj - Ca)$$
$$\text{Or, } F = \dot{m}a\;[(1 + f)\,Cj - Ca\,]$$

EFFICIENCIES:



Propulsive power available to propel aircraft forward is propulsive power and actual power available to propel aircraft forward is thrust power.

I. Propulsive Efficiency / Froude Efficiency :

It is the ratio of useful energy or thrust power to the sum of that energy and unused kinetic energy of jet relative to the earth.

$$\eta_P = \frac{\text{Thrust power}}{\text{Engine output power}}$$

$$= \frac{F \times Ca}{F \times Ca + \frac{1}{2}\dot{m}a\,(C_j - C_a)^2}$$

$$= \frac{F \times Ca}{F \times Ca + \frac{F}{2}\,(Cj - Ca)}$$

$$= \frac{F \times Ca}{F \times Ca + \frac{F \times Ca}{2}\,(\frac{Cj}{Ca} - 1)}$$

$$= \frac{1}{1 + \frac{1}{2}\,(\frac{1}{\alpha} - 1)}$$

$$\boldsymbol{\eta_P = \frac{2\,\alpha}{1 + \alpha}} \qquad \text{where } \alpha = \frac{Ca}{Cj}$$

NOTE:

1. η_P is the measure of effectiveness with which the propelling duct is being used for propelling the aircraft.
2. The above expression for η_P is valid for all air breathing engines.
3. For maximum thrust, $\alpha = 0$ i.e. $\eta_P = 0$.
4. For maximum efficiency, $\alpha = 1$ i.e. $F = 0$.
5. For maximum thrust power,
   Thrust power = F x Ca
   $= \dot{m}a\,(Cj - Ca)Ca$
   $= \dot{m}a\,Cj^2\,(1 - \alpha)\alpha$
   For maximum thrust power, differentiate with respect to α and equate to zero.

$$\frac{dTp}{d\alpha} = \dot{m}a\,Cj^2\,(\alpha\,(-1) + (1 - \alpha)) = 0$$

$$\therefore \alpha = \frac{1}{2} = \frac{Ca}{Cj}$$

$$\therefore Cj = 2\,Ca$$

$$\therefore \quad \boldsymbol{\eta_P = 66.67\ \%}$$

II. THERMAL EFFICIENCY:

$$\eta_T = \frac{\text{Propulsive power}}{\text{Heat power}} = \frac{\frac{1}{2}\dot{m}a\,(Cj^2 - Ca^2)}{\dot{m}f \times CV}$$

$$= \frac{Cj^2\,(1 - \alpha)}{2\,f \times CV} \qquad \text{where, } \alpha = \frac{Ca}{Cj} \text{ and } f = \frac{\dot{m}f}{\dot{m}a}$$

III. OVERALL EFFICIENCY:

$$\eta_O = \frac{\text{Thrust power}}{\text{Heat power}}$$

= propulsive efficiency x thermal efficiency

IV. THRUST SPECIFIC FUEL CONSUMPTION:

$$\text{TSFC} = \frac{\text{mass flow rate of fuel}}{thrust}$$

$$= \frac{\dot{m}f}{F} \times 3600 \qquad \frac{kg}{N-hr}$$

V. THRUST POWER SPECIFIC FUEL CONSUMPTION:

$$\text{TSFC} = \frac{\text{amount of fuel burnt}}{thrust\ power}$$

$$= \frac{\dot{m}f}{F} \times 3600 \qquad \frac{kg}{N-hr}$$

VI. SPECIFIC THRUST:

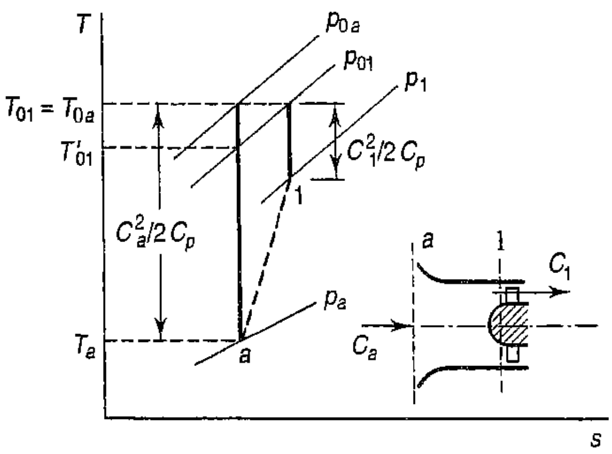
$$F_s = \frac{thrust}{mass\ flow\ rate} = \frac{F}{\dot{m}a} = (C_j - C_a)$$

It provides an indication of relative sizes of engines producing same thrust because dimensions of engine are primarily determined by air flow.

VII. NON-DIMENSIONAL THRUST:

$$\text{Non-Dim Thrust} = \frac{thrust}{speed\ of\ sound} = \frac{F}{a}$$

INTAKE /DIFFUSER EFFICIENCY:



The main function of intake is to minimize the pressure loss upto the compressor phase while ensuring that the flow enters the compressor with uniform pressure and velocity.

The efficiency of diffuser can be expressed in two ways;

1. **Isentropic efficiency:**

$$\eta_{id} = \frac{To1' - Ta}{T01 - Ta}$$

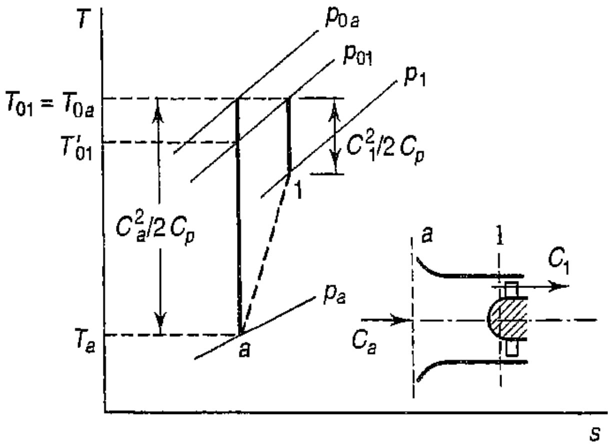
2. **RAM efficiency:**

$$\eta_R = \frac{Po1 - Pa}{P0a - Pa}$$

$$T_{01} = T_{oa} = T_o + \frac{Ca^2}{2\,Cp}$$

1. P_{01} – Pa is referred as RAM pressure rise.
2. Take diffuser efficiency as 0.93 for subsonic
3. η_{id}< 0.93 for supersonic
4. $\frac{P01}{Pa} = \{1 + \frac{\gamma-1}{2} M^2 \eta id\}^\wedge \frac{\gamma}{\gamma-1}$
5. For supersonic intakes :
   Pressure recovery factor should be as high as possible.
   PRF = $\frac{P01}{Pa}$
   If PRF is not given than,
   PRF = $\frac{P01}{Pa} = 1 - 0.075(Ma - 1)^{1.75}$

PROPELLING NOZZLE:



If $\frac{P04}{P5} < \frac{P04}{Pc}$, then unchoked

$\frac{P04}{P5} > \frac{P04}{Pc}$, then choked

Where, Pc = critical pressure

$$\frac{P04}{Pc} = \left[\frac{1}{1 - \frac{1}{\eta in}\left(\frac{\gamma-1}{\gamma+1}\right)}\right]^{\frac{\gamma}{\gamma-1}}$$

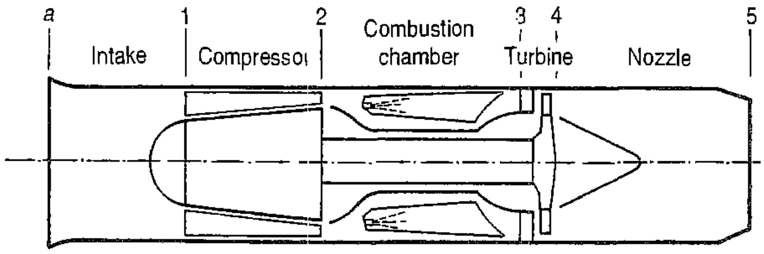
Where, η_{in}= nozzle efficiency =0.95

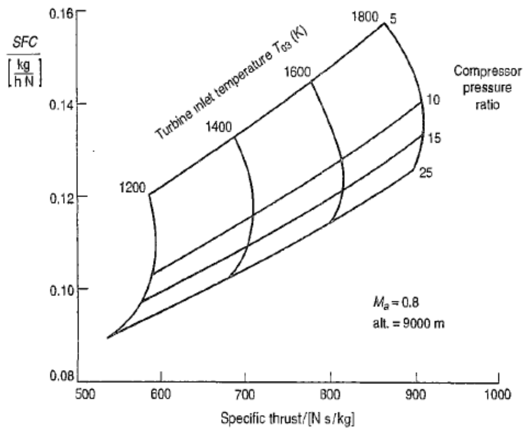
1. $\eta_{iN} = \frac{T04 - T5}{T04 - T5'}$
2. If nozzle is unchoked take $\frac{P04}{P5}$ for further calculation and we have optimum expansion.
3. If nozzle is unchoked, Cj =$\sqrt{2Cp(T04 - T5}$
4. If nozzle is choked take $\frac{P04}{Pc}$ for further calculation.
5. Calculate Tc and ρc
6. If nozzle is unchoked, Cj =$\sqrt{\Upsilon RTc}$
7. Consider pressure thrust in calculating total thrust.

Standard values for engine performance calculations:

1. Heating value of fuel – 43100 KJ/kg
2. Cp(air) - 1.005 KJ/kg K
3. **γ** (air) - 1.4
4. Cp (gas) - 1.107 KJ/kg K
5. **γ** (gas) - 1.33

OPTIMISATION OF TURBOJET ENGINE

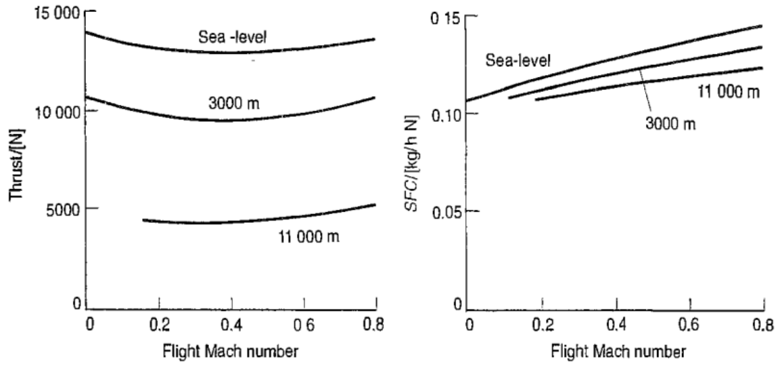




SUBSONIC CRUISE CONDITION

- Basic thermodynamic parameters for the design of turbojet engine are turbine inlet temperature and compressor pressure ratio.
- Thrust is strongly dependent on the value of TIT.
- At constant pressure ratio an increase in TIT will cause some increase in SFC .
- The gain in F_S with increasing temperature is invariably more important than the penalty in increased SFC particularly at high flight speeds where small engine size is essential to reduce both weight and drag .
- The effect of increase in pressure ratio is to reduce SFC.
  - At fixed value of T_{03}, increasing the pressure ratio initially results in an increase in F_s but eventually leads to decrease.
  - The optimum pressure ratio for maximum specific thrust increases as value of TIT increases.

For HIGHER CRUISE CONDITIONS AT SAME ATTITUDE:



- For a given value of pressure ratio and TIT, SFC increases and specific thrust decreases.
- These effects are due to the combination of increase in inlet momentum drag and an increase in compressor work due to rise in compressor inlet temperature.
- Compressor curves for different altitudes show an increase in F_s and on decrease in SFC with increasing altitude due to fall in temperature and the resultant reduction in compressor work.
- Notable effect of increase in design cruise speed is that the optimum compressor pressure ratio for maximum specific thrust is reduced.

REQUIREMENT OF SUPERSONIC AIRCRAFT:

The higher the temperature at compressor inlet and need for higher jet velocity make the use of high turbine inlet temperature desirable and indeed essential for arsenic operation of supersonic aircraft.

VARIATION OF THRUST & SFC WITH FLIGHT CONDITIONS OF TURBOJET ENGINE (PERFORMANCE):

The following curves are obtained for designed point are:

- If the engine was run at fixed rotational speed the compressor pressure ratio (r) and turbine inlet temperature (T_{03}) would change with intake conditions.
- The above curve shows when turbojet engines are operating at maximum rotational speed.
- Thrust decreases significantly with increase in altitude due to decrease in ambient pressure and density.
- Specific thrust increases with altitude due to favourable effect of lower intake temperature.
- SFC decreases with increase in altitude
- With increase of $\dot{m}_a$ at fixed altitudes, the thrust initially decreases due to increase in momentum drag and then starts to increase due to beneficial effects of RAM pressure rise.
    - At supersonic Mach number this increase in thrust is substantial.

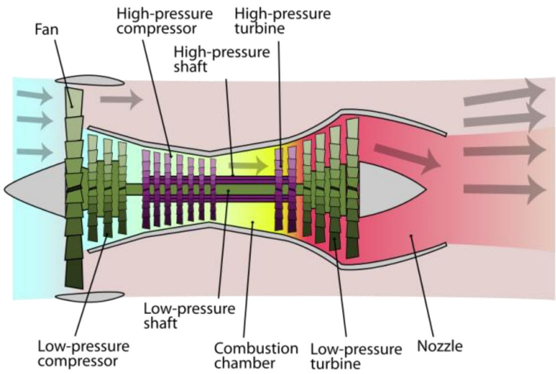
ADVANTAGES OF TURBOJET ENGINE:

- Suitable for long distance flight at higher speeds and altitudes.
- Lower frontal area and shorter landing gears.
- Lower weight per unit thrust at designed speed and altitude.
- Pressure rise through inlet diffuser is significant.
- Reheat can be employed for the increased thrust (After burner).

DISADVANTAGES OF TURBOJET ENGINE:

- Take off run is longer requiring longer runways.
- Specific fuel consumption is comparatively higher at lower speeds and altitude.
- Uneconomical on short at distance flight.
- Lower thrust and propulsive efficiency at lower speeds.

TURBOFAN ENGINE



- The turbofan engine is the combination of turboprop and turbojet combining the advantages of both.
- In the turboprop engine a quantity of air flowing through the propeller is much greater than that passing through the engine, while in turbojet system the entire air passes through the engine.

Working

- Turbofan engine system employs a low pressure ducted fan. The air after passing through the fan is divided into two streams
    1. The primary stream ($\dot{m}_{h}$) goes through the conventional turbo jet engine consisting of compressor, combustion chamber, and turbine and exhaust nozzle.
    2. The secondary stream ($\dot{m}_{a}$) at relatively lower pressure is ducted around the turbojet engine for expansion through the annular fan nozzle.
- Thrust is developed by the bypass air ejecting as cold jet at lower velocities and by primary air ejecting as a hot gas at much higher velocities.
- Thrust produced by the cold jet at lower velocities reduces the noise levels.

BYPASS RATIO

- It is defined as the ratio of flow through the bypass duct (cold stream) to the flow at entry to the high pressure compressor (hot stream)

$$\beta = \frac{\dot{m}c}{\dot{m}h}$$

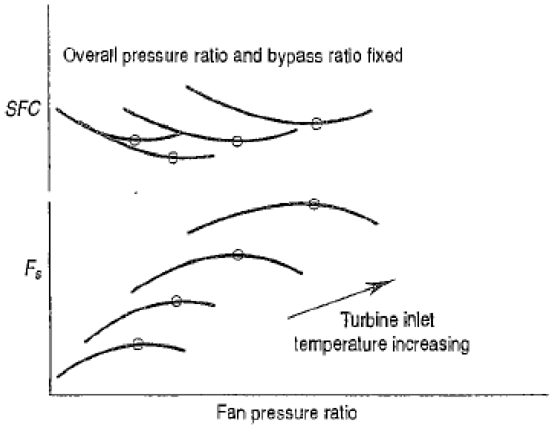
- Thrust assuming both streams are expanded to atmospheric pressure in propelling nozzle.

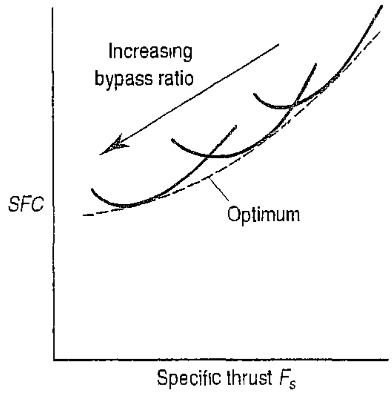
Net thrust, $F = (\dot{m}_h C_{jh} + \dot{m}_c C_{jc}) - (\dot{m}_a C_a)$

REMARKS

- Turbofan improves propulsive efficiency of engine by reducing mean jet velocity particularly operating at high subsonic speeds.
- Lower jet velocity also results in less jet noise.
- As compared to turbo jet, turbofan has lower emissions of nitrogen oxides, unburned hydrocarbons, CO, CO2 etc. because of lower operating temperature in engine cycle.

OPTIMISATION OF TURBOFAN ENGINE:





Designer of turbofan engine has to consider these four parameters:

- Overall pressure ratio
- TIT (stator outlet temperature)
- Bypass ratio (β)
- Fan pressure ratio

This graph is for fixed overall pressure ratio and bypass ratio.

- Consider turbofan engine with OPR & BPR fixed.
- For a particular value of TIT the energy input is fixed.
- For low value of FPR the fan thrust will be small and the work extracted.

From low pressure turbine will also be small .Thus, it energy will be extracted from hot stream and large values of SFC as KE loss in jet is high.

- As, FPR increases fan thrust increases and hot thrust decreases.
- For a given value of TIT, there will be optimum value of FPR for minimum SFC and maximum specific thrust coincides with minimum SFC.

VARIATION OF SFC WITH SPECIFIC THRUST:

- Increase in BPR improves SFC at the expense of significant reduction in specific thrust.
- The optimum FPR decreases with increasing BPR.
- The optimum SFC requires low specific thrust which is particularly important for high BPR turbofan.

ADVANTAGES OF TURBOFAN:

- Short take off role due to increased thrust at low speed .
- Comparatively quitter engine.
- More efficient flow in fan nozzle.
- On account of short length and low speed .
- Weight / unit thrust is higher than turbojet but lower than turboprop.
- Thrust higher than turbojet at low speed.

DISADVANTAGES OF TURBOFAN:

- Increased frontal area hence more drag.
- Separate thrust reversals are required for hot and cold jets if they are separated.

- Specific fuel consumption is higher compared to turboprop.
- Engine is heavier and complicated compared to turbojet.
- Lower speed limit than that of turbojet.

DISADVANTAGES OF TURBOPROP:

- At high speeds due to shocks and flow separation the propeller efficiency decreases rapidly thereby putting a maximum speed limit on the engine.
- It requires a reduction gear which increases the cost of and also consumes certain amount of energy developed by turbine.
- Also requires more space and weight increases.

NOTE:

Turboprop generally operates with nozzle unchoked and in a simple straight through tail plane rather than a convergent nozzle.

THRUST AUGMENTATION

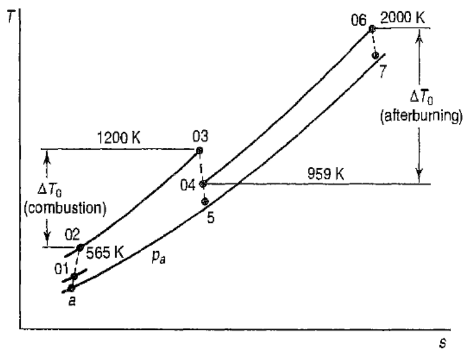
Thrust of a Gas turbine engine can be increased:

- By increasing the mass flow through the engine
- By Increasing the TIT

Requirement for a temporary increase in thrust, example take – off, for accelerations, manoeuvres etc.

Two widely used methods

1. **Liquid injection:**
   - Mixture of water and methanol is used
   - Spraying water into compressor inlet causes evaporation of the water droplets, resulting in extraction of heat from the air, the effect of this is equivalent to a drop in compressor inlet temperature.
   - Reducing the temperature at entry to a turbojet will increase the thrust, due to increase in pressure ratio and mass flow resulting from the effective increase in rotational speed.
2. **Afterburner:**



- Stoichometric combustion is desirable for maximum thrust augmentation
- Assuming choked convergent nozzle , T_7 or T_5 with or without afterburner , jet velocity can be found $\sqrt{\Upsilon R T_c}$ where T_c is given by
  $\frac{T06}{Tc}$ or $\frac{T04}{Tc} = \frac{\gamma + 1}{2}$
- It follows that jet velocity is proportional to $\sqrt{To}$ at inlet to the propelling nozzle.

- The gross momentum thrust, relative to that of the simple turbojet, will be increased in the ratio $\sqrt{\frac{T06}{T04}}$
- Afterburner incorporates a variable area nozzle because of the large change in density of the flow approaching the nozzle resulting from the large change in temperature.
- Variable nozzle is fitted permitting a significant increase in nozzle area. The pressure thrust will also be increased owing to the enlarged nozzle area.

Ideal RAMJET Engine:

A ramjet engine provides a simple, light propulsion system for high speed flight. Unlike a turbojet engine, ramjets and scramjets have no moving parts, only an inlet, a combustor that consists of a fuel injector and a flame holder, and a nozzle.

$$\frac{\mathrm{P0a}}{\mathrm{Pa}} = \left\{1 + \frac{\gamma - 1}{2} Mi^2\right\}^{\frac{\gamma}{\gamma-1}}$$

$$\frac{\mathrm{P0e}}{\mathrm{Pe}} = \left\{1 + \frac{\gamma - 1}{2} Me^2\right\}^{\frac{\gamma}{\gamma-1}}$$

But, $Po_a = Po_e$

So, $\mathbf{M_i = M_e}$

$$\frac{Ci}{\sqrt{\Upsilon RTa}} = \frac{Cj}{\sqrt{\Upsilon RTe}}, \quad C_j = \sqrt{\frac{\mathrm{Te}}{\mathrm{Ta}}}$$

Now, $\frac{\mathrm{T0e}}{\mathrm{Te}} = \left\{1 + \frac{\gamma - 1}{2} Me^2\right\}$

$$\frac{\mathrm{T0a}}{\mathrm{Ta}} = \left\{1 + \frac{\gamma - 1}{2} Mi^2\right\}$$

Therefore, $\frac{\mathbf{Toe}}{\mathbf{Toa}} = \frac{\mathbf{Te}}{\mathbf{Ta}}$