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FORMULA SHEET

for

GATE-AE JET PROPULSION

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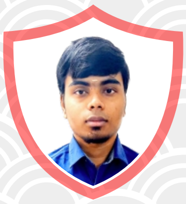

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JET PROPULSION

JET PROPULSION CYCLES

Ideal Cycle:

Net work done.

$W_{net} = c_P(T_{03} - T_{04}) - c_P(T_{02} - T_{01})$

$W_{net} = W_T - W_C$

Where, c_P = specific heat of gas at constant pressure.

T_o = Total temperature

W_T = Work done per unit mass flow in turbine.

W_C = work done per unit mass flow in compressor.

Compression ratio or Expansion Ratio:

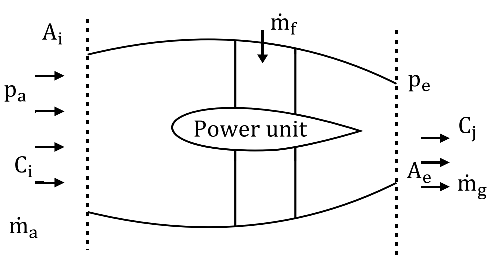
$$r = \left(\frac{T_{02}}{T_{01}}\right)^{\frac{\gamma}{\gamma-1}}$$

$$= \left(\frac{T_{03}}{T_{04}}\right)^{\frac{\gamma}{\gamma-1}}$$

$$r = \frac{p_{02}}{p_{01}} = \frac{p_{03}}{p_{04}}$$

Efficiency: $\eta = 1 - \left(\frac{1}{r}\right)^{\frac{\gamma-1}{\gamma}}$

Thrust Produced by the Jet Engine:



Where,

C_i = Forward speed

$\dot{m}_a$ = Mass flow rate of air

p_a = Atmospheric pressure

A_i = Inlet area

$\dot{m}_f$ = Mass flow rate of fuel

C_j = Jet exhaust speed

p_e = Exit plane pressure.

A_e = Exit plane area.

$$F = \underbrace{\dot{m}_g C_j - \dot{m}_a C_i}_{\text{Momentum thrust}} + \underbrace{(p_e - p_a)Ae}_{\text{Pressure thrust}}$$

$$F = \dot{m}_a[(1+f)C_j - C_i] + (p_e - p_a)Ae$$

Where, $f = \frac{\dot{m}_f}{\dot{m}_a}$ is fuel to air ratio

Optimum Thrust:

$$F_{opt} = \dot{m}_a[(1+f)C_j - C_i]$$

Specific Thrust:

$$F_s = \frac{F}{\dot{m}_a} = (1+f)C_j - C_i + (p_e - p_a)\frac{Ae}{\dot{m}_a}$$

Specific Fuel Consumption (SFC)

(Note: Defined differently)

1. Thrust specific fuel consumption (TSFC)

$$TSFC = \frac{\dot{m}_f}{F}\left(\frac{kg}{(N \cdot s)}\right)$$

$$= \frac{\dot{m}_f}{F} \times 3600\ (kg/(N.hr))$$

$$= \frac{f}{F_5} \times 3600\ (kg/(N.hr))$$

Note: this equation is not valid for turbofan engines.

2. **Power Specific fuel consumption**

$$SFC = \frac{\dot{m}_f}{T.P}\ (kg/(W.hr))$$

$$= \frac{\dot{m}_f}{T.P} \times 3600\ (kg/(W.hr))$$

Where, T.P is thrust power $T.P = F.C_i$

Propulsive Efficiency:

$$\eta_p = \frac{\text{Thrust power}}{\text{Propulsice power}}$$

$$= \frac{F \cdot C_i}{\frac{1}{2}\dot{m}_a\left(C_j^2 - C_i^2\right)}$$

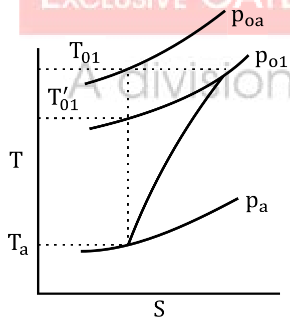
$$\eta_p = \frac{2\alpha}{1+\alpha}$$

where, $\alpha = \frac{C_i}{C_j}$

Intake Performance:

1. **Isentropic efficiency:**

$$\eta_{in} = \frac{T'_{01} - T_a}{T_{01} - T_a}$$



2. **Ram Efficiency:**

$$\eta_R = \frac{p_{01} - p_a}{p_{0a} - p_a}$$

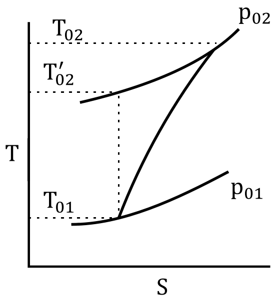
Ram pressure rise $= p_{01} - p_a$

Pressure recovery factor $= \frac{p_{01}}{p_{0a}}$

Compressor Performance:

Adiabatic/Isentropic efficiency

$$\eta_c = \frac{T'_{02} - T_{01}}{T_{02} - T_{01}}$$



$$\eta_c = \frac{T_{01}\left(\frac{T'_{02}}{T_{01}} - 1\right)}{T_{02} - T_{01}}$$

$$\eta_c = \frac{T_{01}\left(\pi_c^{\frac{\gamma-1}{\gamma}} - 1\right)}{T_{02} - T_{01}}$$

Where, $\pi_c = \frac{p_{02}}{p_{01}}$

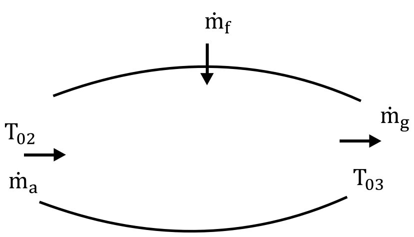
Polytropic Efficiency

$$\eta_c = \frac{\pi_c^{\frac{\gamma-1}{\gamma}} - 1}{\pi_c^{\frac{\gamma-1}{\eta_{\infty,c}\gamma}} - 1}$$

where, $\eta_{\infty,c} = \frac{\gamma - 1}{\gamma} \cdot \frac{n}{n-1}$

And $n \rightarrow$ polytropic index.

Combustion Chamber Performance:



$$\dot{m}_g c_{p_g} T_{03} = \dot{m}_a c_{p_a} + T_{02} + \eta_b\,\dot{m}_f Q_{cv}$$

$$f = \frac{c_{p_g}T_{03} - c_{p_a}T_{02}}{\eta_b Q_{cv} - c_{p_g}T_{03}}$$

where, $\dot{m}_g = \dot{m}_a + \dot{m}_f$

η_b = Combustion efficiency

c_{p_a}, c_{p_g} = Specific heat at constant pressure for air and gas, respectively.

Q_{cv} = Lower heating value/Calorific value of fuel.

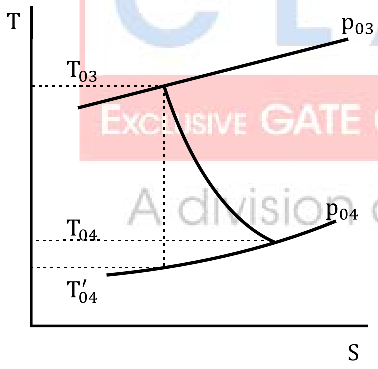
Turbine Performance:

Adiabatic/Isotropic Efficiency:

$$\eta_T = \frac{T_{03} - T_{04}}{T_{03} - T'_{04}}$$

$$\eta_T = \frac{T_{03} - T_{04}}{T_{03}\left(1 - \left(\frac{1}{\pi_t}\right)^{\frac{\gamma-1}{\gamma}}\right)}$$

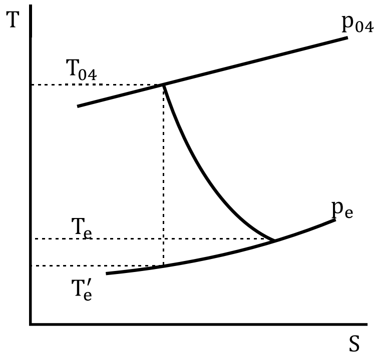
Where, $\pi_t = \frac{p_{03}}{p_{04}}$



Nozzle Performance:

Adiabatic efficiency:

$$\eta_{noz} = \frac{T_{04} - T_e}{T_{04} - T'_e}$$



For chocking

$$\frac{p_{04}}{p_e} < \frac{p_{04}}{p_a}$$

Where, p_e = nozzle exit plane pressure.

T_e = nozzle exit plane temperature.

p_a =Ambient pressure

p_c = Chocked pressure

$$\frac{p_{04}}{p_c} = \left[\frac{1}{1 - \frac{1}{\eta_{noz}}\frac{\gamma - 1}{\gamma + 1}}\right]^{\frac{\gamma}{\gamma-1}}$$

$p_e = p_a$, for optimum expansion

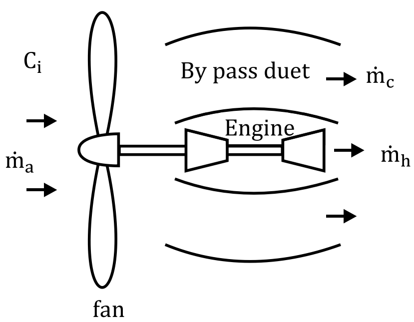
For choked flow

$$C_j = \sqrt{\gamma R T_c}$$

For unchoked flow

$$C_j = \sqrt{2c_p(T_{04} - T_e)}$$

Turbofan Engine Analysis:



By pass ratio $(\beta) = \frac{\dot{m}_c}{\dot{m}_h}$

$$= \frac{\text{Mass flow of clod air}}{\text{mass flow of hot air}}$$

$\dot{m}_a = \dot{m}_c + \dot{m}_h$

$\dot{m}_h = \frac{\dot{m}_a}{\beta + 1}, \quad \dot{m}_c = \frac{\beta\, \dot{m}_a}{\beta + 1}$

Where, $\dot{m}_a$ = air mass flow rate

$\dot{m}_c$ = Bypass flow rate or cold flow rate

$\dot{m}_h$ = hot flow rate

Thrust:(Assuming Optimum Thrust)

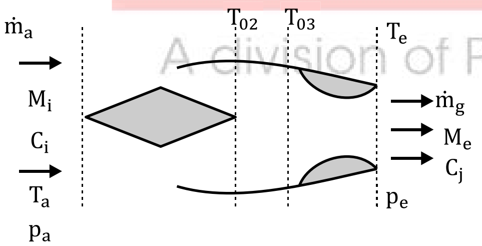
$F = F_{cold} + F_{hot}$

$= \dot{m}_h[C_{jh}] + \dot{m}_c[C_{jc}] - \dot{m}_a\, C_i$

$$F = \dot{m}_a\left[\frac{1}{\beta + 1} C_{jh} + \frac{\beta}{\beta + 1} C_{jc}\right] - \dot{m}_a C_i$$

$$F_s = \frac{F}{\dot{m}_a} = \frac{C_{jh}}{\beta + 1} + \frac{\beta}{\beta + 1} C_{jc} - C_i$$

Ramjet Engine Performance:



Ideal Ramjet:

$M_i = M_e$

$$\frac{C_i}{\sqrt{\gamma R T_a}} = \frac{C_j}{\sqrt{\gamma_g R_g T_e}}$$

Fundamental of Rotating Machines

Euler's Energy Equation

$$E = \frac{P}{\dot{m}} = W = u_2 C_{t_2} - u_1 C_{t_1}$$

Where, P → Power

$\dot{m}$ → mass flow rate of the fluid

W → work done on the fluid per unit mass flow rate.

u → Peripheral velocity/blade velocity vector.

E → Energy transfer

Modified form:

$$E = W = \frac{C_2^2 - C_1^2}{2} + \frac{u_2^2 - u_1^2}{2} + \frac{w_1^2 - w_2^2}{2}$$

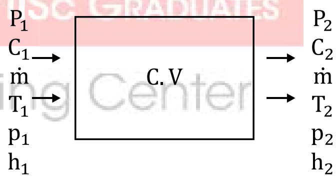
$\vec{C}$ → Absolute velocity vector

$\vec{w}$ → Relative velocity vector

Velocity vector relation for rotating machines

$\vec{C} = \vec{u} + \vec{w}$

Control volume analysis to find work done:



$W = h_{02} - h_{01}$

$W = c_p(T_{02} - T_{01})$

Important non-dimensional Variables for turbomachinery:

$$\left(\frac{p_{02}}{p_{01}}, \frac{T_{02}}{T_{01}}, \frac{\dot{m}\sqrt{RT_{01}}}{D^2 P_{01}}, \frac{ND}{\sqrt{RT_{01}}}\right)$$

COMPRESSOR

Centrifugal Compressor:

Work done: $W_c = u_2 C_{t2} - u_1 C_{t1}$

$$u = \frac{\pi DN}{60}$$

Where, D → Diameter

N → revolution per minute

C_t → tangential component of absolute velocity

For axial entry of fluid at the entry

$W_c = u_2 C_{t_2}$

$W_c = \sigma\, u_2^2$

$\sigma = \frac{C_{t_2}}{u_2}$ called slip factor

$0 < \sigma \le 1$

$W_c = \Omega\sigma u_2^2$

Ω → Power input factor $\Omega \ge 1$

Efficiency:

$$\eta_c = \frac{T_{01}\left(\pi_c^{\left(\frac{\gamma-1}{\gamma}\right)} - 1\right)}{T_{02} - T_{01}}$$

$$\pi_c = \left[1 + \frac{\eta_c}{T_{01}}\,(T_{02} - T_{01})\right]^{\frac{\gamma}{\gamma-1}}$$

$$W_c = c_p(T_{02} - T_{01}) = \Omega\sigma u_2^2$$

$$\pi_c = \left[1 + \frac{\eta_c}{T_{01}}\frac{\Omega\sigma u_2^2}{c_p}\right]^{\frac{\gamma}{\gamma-1}}$$

Mass Flow Rate Calculation:

$\dot{m}_a = (\pi d b)\rho_2 C_{r_2}$

At the exit of centrifugal compressor

Where, d → diameter of impeller

b → width of the impeller blade

ρ_2 → Density of air at the impeller exit

C_{r_2} → Radial velocity at the exit

Axial Flow Compressor:

Work done, $W_c = u\left(C_{t_2} - C_{t_1}\right)$

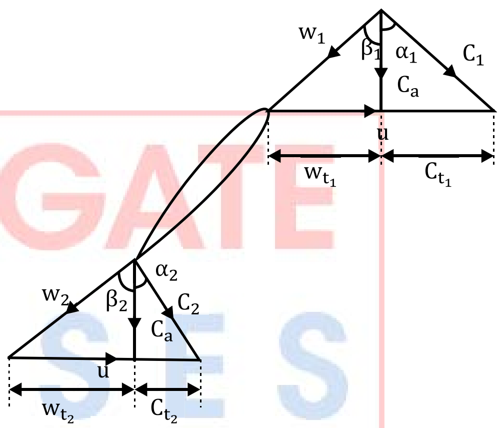
$$= uC_a(\tan\alpha_2 - \tan\alpha_1)$$

$W_c = uC_a(\tan\beta_1 - \tan\beta_2)$

Where, α_1, α_2 → Absolute air angles at the entry and exit of stage. Measured with respect to axial velocity.

β_1, β_2 → Relative air angles/Blade angles at the entry and exit of the stage.

Velocity Triangle:



$u = C_{t_1} + w_{t_1} = C_{t_2} + w_{t_2}$

$$\frac{u}{C_a} = \tan\alpha_1 + \tan\beta_1$$

$$\frac{1}{\phi} = \tan\alpha_2 + \tan\beta_2$$

Where, $\phi = \frac{C_a}{U}$ called flow co-efficient

$W_c = \Omega u C_a(\tan\beta_1 - \tan\beta_2)$

$W_c = \Omega u^2 \phi(\tan\beta_1 - \tan\beta_2)$

Ω → Power input factor.

Degree of Reaction (R):

$$R = \frac{h_2 - h_1}{h_3 - h_1}$$

$$R = \frac{\phi}{2}(\tan\beta_1 + \tan\beta_2)$$

For 50% reaction stage

$$\left.\begin{aligned} R &= 0.5 \\ \alpha_1 = \beta_2, \alpha_2 &= \beta_1 \\ C_1 = w_2, C_2 &= w_1 \end{aligned}\right\}$$ Symmetric velocity triangles at the entry and exit of the stage.

Mass Flow Calculations:

$$\dot{m}_a = \rho C_a \frac{\pi}{4}(D_2^2 - D_1^2)$$

$$\dot{m}_a = \rho C_a \pi d_m h$$

$D_2 \to$ tip diameter

$D_1 \to$ hub diameter

$$\dot{m}_a = P C_a \pi d_m h$$

$d_m \to$ Mean diameter

$h \to$ Height of the blade

Stage Efficiency:

$$\eta_{c_s} = \frac{T_{01}\left(\pi_{c_s}^{\frac{\gamma-1}{\gamma}} - 1\right)}{(T_{02} - T_{01})_{stage}}$$

$$\pi_{cs} = \left[1 + \frac{\eta_{cs}}{T_{01}}(T_{02} - T_{01})_{stage}\right]^{\frac{\gamma}{\gamma-1}}$$

$$\pi_{cs} = \left[1 + \frac{\eta_{cs}}{T_{01}}\frac{\Omega u C_a(\tan\beta_1 - \text{tab}\,\beta_2)}{c_p}\right]^{\frac{\gamma}{\gamma-1}}$$

TURBINE

Axial Flow Turbine:

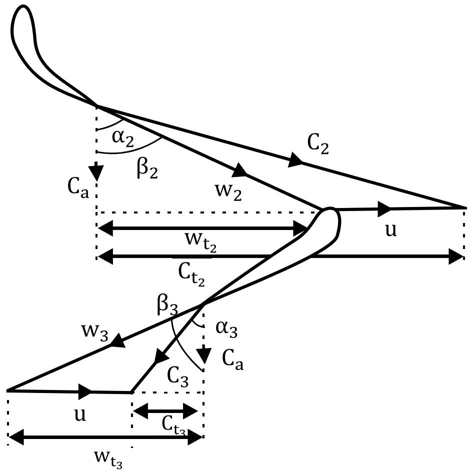
Stage work done:

$$W_T = u(C_{t_2} + C_{t_3})$$

$$W_T = u C_a(\tan\alpha_2 + \tan\alpha_3)$$

$$W_T = u C_a(\tan\beta_2 + \tan\beta_3)$$

Stage Velocity Triangle



$$u = C_{t_2} - w_{t_2} = w_{t_3} - C_{t_3}$$

$$u = C_a(\tan\alpha_2 - \tan_{\beta_2})$$

$$\Rightarrow \frac{1}{\phi} = \tan\alpha_2 - \tan\beta_2 = \tan\beta_3 - \tan\alpha_3$$

Blade Loading Co-efficient(ψ):

$$\psi = \frac{W_T}{u^2}$$

$$\psi = \phi(\tan\beta_2 + \tan\beta_3)$$

$$= \phi\,(\tan\alpha_2 + \tan\alpha_3)$$

Efficiency of Stage:

$$\eta_{T_s} = \frac{T_{03} - T_{04}}{T_{03}\left(1 - \left(\frac{p_{04}}{p_{03}}\right)^{\frac{\gamma-1}{\gamma}}\right)}$$

$$T_{03} - T_{04} = \eta_{T_s} T_{03}\left(1 - \left(\frac{1}{\pi_t}\right)^{\frac{\gamma-1}{\gamma}}\right)$$

$$T_{03} - T_{04} = \frac{u C_a(\tan\beta_2 + \tan\beta_3)}{C_p}$$

Degree of Reaction (R)

$$R = \frac{\phi}{2}(\tan\beta_3 - \tan\beta_2)$$

$$R = \frac{1}{2} + \frac{\phi}{2}(\tan\beta_3 - \tan\alpha_2)$$

$$R = 1 + \frac{\phi}{2}(\tan\alpha_3 - \tan\alpha_2)$$

For 50% reaction stage

$$\left.\begin{aligned} R &= 0.5 \\ \alpha_2 = \beta_3, \alpha_3 &= \beta_2 \\ C_2 = w_3, C_3 &= w_2 \end{aligned}\right\}$$ Stage velocity triangle at the entry and exit are anti-symmetric

COMBUSTION

Combustion Chamber

Performance:

Pressure loss factor:

$$PLF = \frac{\Delta p_o}{\left(\frac{\dot{m}_a^2}{2\rho A_m^2}\right)} = K_1 + K_2\left(\frac{T_{03}}{T_{02}} - 1\right)$$

Where, K_1 → Cold has co-efficient.

K_2 → Hot loss co-efficient

T_{03} → Combustion exit temperature

T_{02} → Combustion entry temperature

Δp_o → Total pressure loss

$\dot{m}_a$ → Mass flow rate

ρ → density at the entry

A_m → Maximum cross-section area of combustion chamber.

Combustion Chemistry:

Assuming Hydrocarbon fuel

$$C_xHy + \left(x + \frac{y}{4}\right)(O_2 + 3.76\,N_2) \rightarrow xCO_2 + \frac{y}{2}H_2O + \left(x + \frac{y}{4}\right)3.76\,N_2 + \text{Energy}\uparrow$$

Stoichiometric Fuel-to-Air Ratio (f_s):

$$f_s = \frac{\sum_{fuel}(\text{Molecular weight}) \times \text{no of moles}}{\sum_{air}(\text{Molecular weight}) \times \text{no of moles}}$$

$$f_s = \frac{12 \times x + 1 \times y}{32 \times \left(x + \frac{y}{4}\right) + 3.76 \times 28 \times \left(x + \frac{y}{4}\right)}$$

For Alkanes, $C_x\,H_y \rightarrow C_n\,H_{2n+2}$

$$f_s = \frac{7n + 1}{34.32\,(3n + 1)}$$

Note: This expression is valid only for alkanes.

Ex: Ethane, Methane etc…

Equivalence Ratio (ϕ):

$$\phi = \frac{f_{actual}}{f_{stoichiometric}}$$

Note: $\phi < 1$ → Fuel lean combustion

$\phi > 1$ Fuel rich combustion

*****

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OUR COURSES

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