APPLIED THERMODYNAMICS

Gas Turbine Engines
(Module IV)

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List of Topics

1. Gas Turbine Engine – Components and Thermal Circuit Arrangement
2. Gas Turbine Performance Cycle – I
3. Gas Turbine Performance Cycle – II
4. Real Gas Turbine Performance Cycle
5. Aircraft Propulsion Cycle – I
6. Aircraft Propulsion Cycle – II

Lecture 5

Aircraft Propulsion Cycle – I

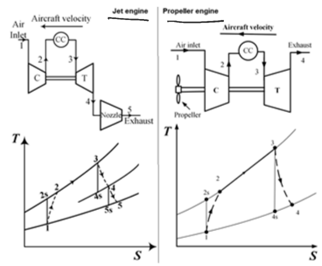
- Performance Criteria
- Simple Turbojet Engine
- Thrust on a Turbojet Engine

Aircraft Propulsion Cycle

- The aircraft gas turbine cycles differ from the shaft power cycle in a sense that the power output is in the form of "thrust".
- Turbojet/Turbofan engines and Turboprop engines use gas turbine cycles for thrust generation.
- Propelling nozzles and propeller are integral part of these engines.
- Forward speed and altitude, power to weight ratio are considered for performance.
- Gas turbine engines for aircraft propulsion differs from IC engines for its essential requirements such as take-off, climb, cruise and maneuvering.
- Long range commercial aircraft must have low SFC at cruise speed and altitude while thrust levels are decided at take-off condition.
- The family of propulsion engines are, piston engine, turbo-prop engine, turbo-jet engine, turbo-fan engine, ram-jet engine and scram-jet engine in the order of increasing speed (subsonic $M < 1$ to hypersonic $M > 5$).

Aircraft Propulsion Cycle

- In a jet engine, the propulsion nozzle finds its place in place of LP turbine.
- The aircraft is powered by reactive thrust of jet of gases leaving the nozzle and the high velocity jet is obtained at the expense of enthalpy drop.
- The turbine develops enough power to drive the compressor and overcome mechanical losses.
- The other variant of jet engine uses turbine power to drive propeller and it is known as turbo-prop engine.



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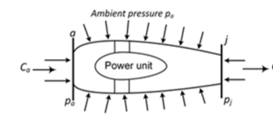
Performance Criteria

- Consider the schematic diagram of a propulsive duct in which the air enters the intake with a certain velocity (equal and opposite to the forward speed of the aircraft).
- The power unit (gas turbine engine) accelerates the air so that it leaves as jet at higher velocity.
- With mass flow rate to be constant, the net thrust is due to the rate of change of momentum, known as gross momentum thrust and intake momentum drag.
- If the exhaust gases are not expanded completely to ambient pressure, the pressure in the exit plane will be higher and there will be an additional thrust resulting due to pressure difference (pressure thrust).
- Thus, the total thrust is the sum of "momentum thrust and pressure thrust".

C_a: Intake air velocity; C_j: Exit jet velocity; A_j: Jet exit area
mC_a: Intake momentum drag; mC_j: Gross momentum thrust
$m(C_j - C_a)$: Momentum thrust; $A_j(p_j - p_a)$: Pressure thrust
Net thrust, $F = m(C_j - C_a) + A_j(p_j - p_a)$



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Performance Criteria

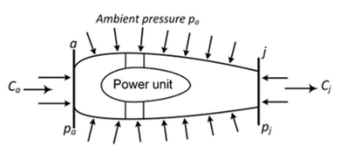
Propulsive efficiency:

- It is defined as the ratio of useful propulsive energy (or thrust power) to the sum of that energy and unused kinetic energy of the jet. It is also called as "Froude efficiency".
- It should be emphasized that unused enthalpy of the jet is ignored while calculating the propulsive efficiency.

$F = m(C_j - C_a)$; (without considering pressure thrust)

$$\eta_p = \frac{mC_a(C_j - C_a)}{m\left[C_a(C_j - C_a) + \frac{1}{2}(C_j - C_a)^2\right]} = \frac{2}{1 + (C_j/C_a)}$$

$C_a = 0 \Rightarrow F \to$ maximum; $\eta_p \to 0$
$C_a = C_j \Rightarrow F \to 0$; $\eta_p \to$ maximum
$\Rightarrow C_j > C_a$ (But difference should not be high)



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Performance Criteria

Propulsive efficiency:

- This concept leads to the family of propulsion unit development in the order of increase in jet velocity and decrease in mass flow rate suitable for aircraft at designed cruise speed.
  - ➢ Piston engine
  - ➢ Turboprop engine
  - ➢ Turbojet engine
  - ➢ Turbofan engine
  - ➢ Ramjet engine
  - ➢ Scramjet engine
- The choice of power unit depends on the required cruise speed, desired range of aircraft, maximum rate of climb and thrust/fuel consumption.
- The propulsive efficiency is a measure of the effectiveness with which the propulsive duct is used for propelling the aircraft.

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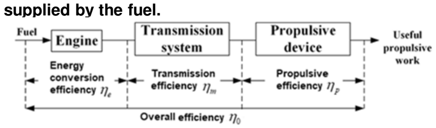
Performance Criteria

Energy conversion efficiency and Overall efficiency:

- The rate of energy supplied by the fuel is converted to the useful kinetic energy of propulsion and unusable enthalpy of the jet.
- "Energy conversion efficiency" is defined as the ratio of kinetic energy of propulsion to the energy supplied by the fuel.
- "Overall efficiency" is the ratio of useful work done to overcome drag to the energy supplied by the fuel.



$$F = m\left(C_j - C_a\right); \quad \text{(without considering pressure thrust)}$$

$$\eta_e = \frac{\frac{1}{2}m\left(C_j^2 - C_a^2\right)}{m_f Q_{net}}; \quad \eta_0 = \frac{mC_a\left(C_j - C_a\right)}{m_f Q_{net}} = \frac{F C_a}{m_f Q_{net}}; \quad \eta_p = \frac{mC_a\left(C_j - C_a\right)}{m\left[C_a\left(C_j - C_a\right) + \frac{1}{2}\left(C_j - C_a\right)^2\right]}$$

$$m\left[C_a\left(C_j - C_a\right) + \frac{1}{2}\left(C_j - C_a\right)^2\right] = m\left[\frac{2C_aC_j - 2C_a^2 + C_j^2 + C_a^2 - 2C_aC_j}{2}\right] = \frac{1}{2}m\left(C_j^2 - C_a^2\right)$$

$$\Rightarrow \eta_p = \frac{mC_a\left(C_j - C_a\right)}{\eta_e\left(m_f Q_{net}\right)} = \frac{\eta_0}{\eta_e} \quad \Rightarrow \eta_0 = \eta_e\,\eta_p; \quad \eta_0 = \eta_e\,\eta_p\,\eta_m$$

Performance Criteria

Specific fuel consumption and specific thrust:

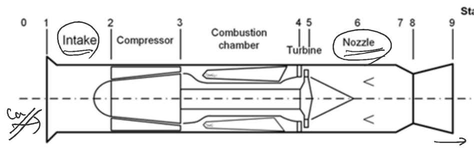
- The efficiency of an aircraft power plant is intricately related to the speed.
- In general, the engine performance is quoted at two operating conditions:
  - ➢ Sea level performance at maximum power and maximum turbine inlet temperature
  - ➢ Takeoff requirement and cruise performance at optimum cruise speed and intended altitude of operation
- The overall efficiency is redefined in terms of specific fuel consumption.
- The thrust per unit mass flow of air is known as "specific thrust".
- The dimensions of the engine is primarily determined by the air flow rate and it provides indication of relative size (mainly frontal area – drag dependent) of the engine producing same thrust.

$$\eta_0 = \frac{mC_a\left(C_j - C_a\right)}{m_f Q_{net}} = \frac{F C_a}{m_f Q_{net}} = \frac{C_a}{(SFC)} \times \frac{1}{Q_{net}}$$

$$f = \frac{m_f}{m}; \; F_s = \frac{f}{SFC}; \; SFC: (\mathrm{kg/h.N}); \; F_s: (\mathrm{N.s/kg})$$

Simple Turbojet Engine

- A simple turbojet engine operating on ideal cycle has turbine work just sufficient to drive the compressor and remaining part is utilized for propelling.
- Since there is significant forward speed, the intake and propelling nozzle are considered as a separate component.
- Typically, subsonic aircraft cruise at Mach 0.8 to 0.85 while cruising Mach number for supersonic aircraft is 2 to 2.5. So, compressors require the flow to enter the first stage at axial Mach number 0.4 to 0.5.
- During takeoff (zero forward speed), engine operates at maximum power and air flow. In such situations, intake caters wide range of operating conditions.

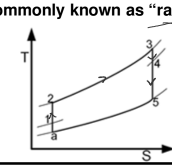


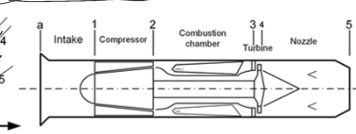
Station	Location
0	Free stream
1	Engine intake
2	Compressor inlet
3	Compressor delivery
4	Turbine inlet
5	Turbine exit
6	Front face of mixer or afterburner
7	Nozzle inlet
8	Nozzle throat
9	Nozzle exit (divergent only)

Simple Turbojet Engine

Intake efficiency:

- Generally, intakes are treated as an adiabatic duct.
- There is loss of stagnation pressure due to shock waves at supersonic speeds in the intake.
- The intake requirement is to minimize pressure loss up to compressor face by ensuring uniform pressure and velocity at all flight condition.
- At low forward speeds (static condition), the 'intake' acts as a nozzle (flow accelerates) and at normal forward speed, 'intake' acts as diffuser (flow deceleration) by virtue of its geometry.
- Thus, pressure always rises in the intake and it aircraft terminology, it is commonly known as "ram pressure rise".

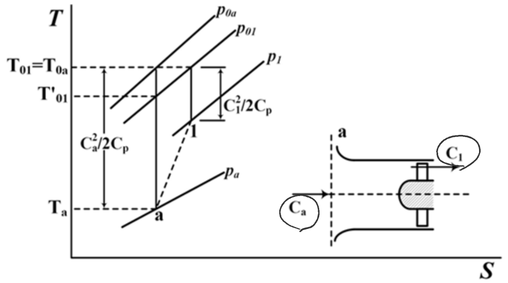




Simple Turbojet Engine

Intake efficiency:

- **Isentropic efficiency (defined in terms of temperature rise) and Ram efficiency (expressed in terms of pressure rise) are two methods by which the efficiency of intake system are analyzed in a turbojet engine.**
- **It is a easier approach to measure pressure and hence "ram efficiency" takes advantage over isentropic efficiency.**

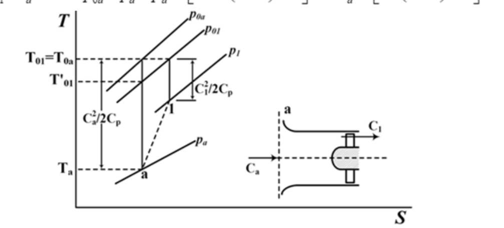


Simple Turbojet Engine

Intake efficiency:

- **When air velocity approaches zero, there is no stagnation pressure or temperature loss. It is not a serious concern because the flow is in accelerating stage so that effect of friction is small.**
- **For subsonic intakes, both ram efficiency and isentropic efficiency are independent of inlet Mach number (up to 0.8). Its typical value is 0.93.**

$$\eta_i = \frac{T'_{01}-T_a}{T_{01}-T_a};\ \ \eta_r = \frac{p_{01}-p_a}{p_{0a}-p_a};\ \frac{p_{01}}{p_a} = \left[1+\eta_i\left(\frac{\gamma-1}{2}\right)M_a^2\right]^{\frac{\gamma}{\gamma-1}};\ \frac{T_{01}}{T_a} = \left[1+\left(\frac{\gamma-1}{2}\right)M_a^2\right]$$

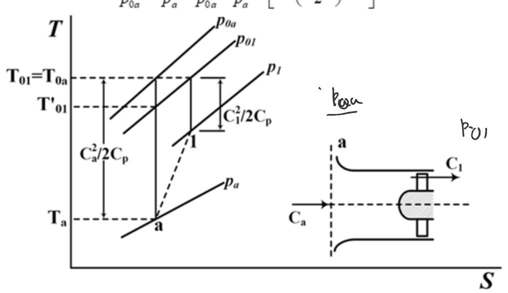


Simple Turbojet Engine

Pressure recovery factor:

- **Another practice is to quote the efficiency of the intake system through pressure recovery factor (i.e. the ratio stagnation pressure available at compressor inlet to the ambient stagnation pressure).**

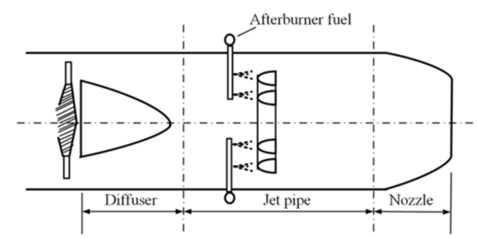
$$\frac{p_{01}}{p_{0a}} = \frac{p_{01}}{p_a}\times\frac{p_a}{p_{0a}};\ \frac{p_{01}}{p_a} = \left[1+\left(\frac{\gamma-1}{2}\right)M_a^2\right]^{\frac{\gamma}{\gamma-1}}$$



Simple Turbojet Engine

Propelling nozzle:

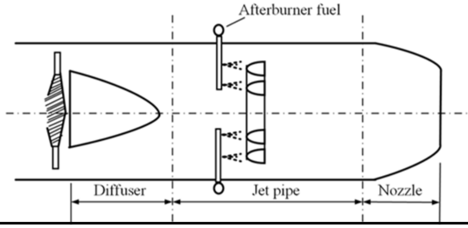
- **It refers to the component of engine system in which the working fluid is expanded to high-velocity jet.**
- **Depending on the location of the engine in the aircraft, the propelling nozzle finds it compromising position. Its shape is usually convergent type.**
- **The thermodynamic analysis is based on the approach through isentropic efficiency and specific thrust coefficient.**



Simple Turbojet Engine

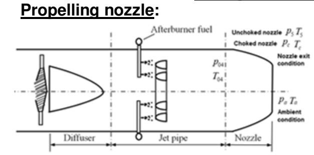
Propelling nozzle:

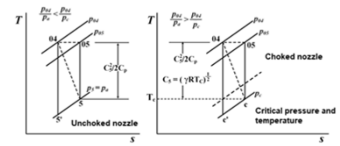
- Isentropic efficiency is expressed in terms of ratios of temperature difference between actual expansion to isentropic expansion. Typically, its value is 0.95.
- Specific thrust coefficient is the ratio of actual specific gross thrust to the thrust that results from isentropic flow.
- Velocity coefficient is defined as the ratio of actual to isentropic jet velocity.
- When the expansion is complete to ambient pressure, the specific thrust coefficient becomes same as the velocity coefficient.



Simple Turbojet Engine

Propelling nozzle:





Specific thrust coefficient, $K_F = \dfrac{mC_5 + A_5(p_5 - p_a)}{m}$; Velocity coefficient, $C_c = \dfrac{C_j}{C_j'}$

$$\frac{p_{04}}{p_a} < \frac{p_{04}}{p_c} \Rightarrow K_F = C_c; \quad \frac{p_{04}}{p_c}: \text{Critical ratio, } \frac{p_c}{p_{04}} = \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}}, \frac{T_c}{T_{04}} = \left(\frac{2}{\gamma+1}\right); A_5 = \frac{m}{\rho_c C_c}$$

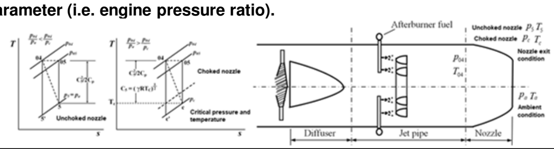
$$\eta_j = \frac{T_{04}-T_5}{T_{04}-T_5'}; \quad \frac{p_c}{p_{04}} = \left(\frac{T_c'}{T_{04}}\right)^{\frac{\gamma}{\gamma-1}} = \left[1 - \frac{1}{\eta_j}\left(1 - \frac{T_c}{T_{04}}\right)\right]^{\frac{\gamma}{\gamma-1}}$$

$$\eta_j = \frac{T_{04}-T_5}{T_{04}-T_5'}; \quad T_{04} - T_5 = \eta_j T_{04}\left[1 - \left(\frac{1}{p_{04}/p_5}\right)^{\frac{\gamma-1}{\gamma}}\right]; \quad \eta_j = K_F^2; \text{ Pressure thrust}: A_5(p_5 - p_a)$$

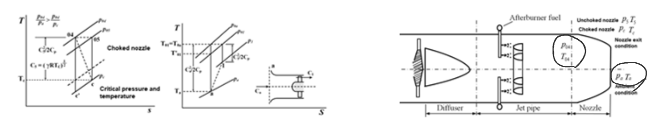
$$\frac{T_{04}}{T_5} = \frac{T_{05}}{T_5} = 1 + \left(\frac{\gamma-1}{2}\right)M_5^2; \quad \frac{T_{04}}{T_c} = \frac{\gamma+1}{2}; \quad \frac{p_{04}}{p_c} = \frac{1}{\left[1 - \frac{1}{\eta_j}\left(\frac{\gamma-1}{\gamma+1}\right)\right]^{\frac{\gamma}{\gamma-1}}}$$

Thrust on a Turbojet engine

- One of the essential requirement for jet engine is the accurate indication of available thrust, particularly for take-off in critical conditions. There is no direct method for this quantification.
- The thrust variation is controlled by fuel flow which is limited by factors such as, maximum permissible values of rotational speed, turbine inlet temperature and fuel flow rate.
- In a simple turbojet engine with fixed area convergent nozzle, the thrust is related to pressure ratio across the nozzle.
- At take-off condition, the aircraft is stationary and the nozzle is assumed to choked for which thrust can be calculated through simple measurable parameter (i.e. engine pressure ratio).



Thrust on a Turbojet engine



$$F = mC_5 + A_5(p_5 - p_a) = \rho_5 A_5 C_5^2 + A_5(p_5 - p_a) \Rightarrow F = \left(\frac{2c_p}{RT_5}\right)p_5 A_5(T_{04} - T_5) + A_5(p_5 - p_a)$$

$$\Rightarrow F = \left[2\left(\frac{\gamma}{\gamma-1}\right)A_5\left(\frac{p_5}{p_{04}}\right)\left(\frac{p_{04}}{p_a}\right)p_a\left(\frac{T_{04}}{T_5} - 1\right)\right] + A_5 p_a\left(\frac{p_5}{p_{04}}\frac{p_{04}}{p_a} - 1\right)$$

$$m = \rho_5 A_5 C_5; \; \rho_5 = \frac{p_5}{RT_5}; \; C_5^2 = 2c_p(T_{04} - T_5); \frac{c_p}{R} = \frac{\gamma}{\gamma-1}$$

Critical pressure and temperature ratios: $\dfrac{p_{04}}{p_5} = \left(\dfrac{\gamma+1}{2}\right)^{\frac{\gamma}{\gamma-1}}; \dfrac{T_{04}}{T_5} = \left(\dfrac{\gamma+1}{2}\right)$

$$\Rightarrow \frac{F}{A_5 p_a} = \frac{p_{04}}{p_a}\left[\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}}(\gamma+1)\right] - 1 = 1.2594\left(\frac{p_{04}}{p_a}\right) - 1; \quad \gamma = 1.33$$

$$\Rightarrow \frac{\left(\frac{F}{A_5 p_a} + 1\right)}{RPR} = 1.2594\left(\frac{p_{04}}{p_a}\right) = 1.2594(EPR); \; NPR, \frac{p_{04}}{p_a} = \left(\frac{p_{04}}{p_{01}}\right)\left(\frac{p_{01}}{p_a}\right) = EPR \times RPR$$

NPR: Nozzle pressure ratio; EPR: Engine pressure ratio; RPR: Ram pressure ratio

Numerical Problems

Q1. Determine the specific thrust, fuel consumption for a simple turbojet engine with following specification: compressor pressure ratio: 8, turbine inlet temperature: 1250 K, Isentropic efficiency: intake (0.93), compressor (0.85), turbine (0.9), propelling nozzle (0.95), mechanical and combustion efficiency: 0.98, combustion chamber pressure loss: 4% of compressor delivery pressure, exhaust pressure loss: 0.03 bar, ambient condition: 0.26 bar, 220 K; Mach number: 0.8.

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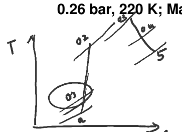

a – 01 — Intake
01 - 02 — Comp.
02 - 03 comb.
03 - 04 → Turbine.
04 - 05 → Nozzle.

Ambient → $p_a = 0.26$ bar.
$T_a = 220$ K.

$a = \sqrt{\gamma R T} = 297$ m/s
$\gamma = 1.4$
$M = 0.8$.
$R = 287$ J/kg
$\frac{C_a}{a} = 0.8$
$T_a = 220$ K.
$\Rightarrow C_a = 238$ m/s.
$c_p = 1.005$ kJ/kg

Intake $T_{01} = T_a + \frac{C_a^2}{2c_p}$. $\frac{C_a^2}{2c_p} = 28$ K.

$\Rightarrow T_{01} = 248$ K. $\eta_i = 0.93$.

$\frac{p_{01}}{p_a} = \left[1 + \eta_i \frac{C_a^2}{2c_p T_a}\right]^{\frac{\gamma}{\gamma-1}}$

$\Rightarrow \frac{p_{01}}{p_a} = 1.48$.

$\Rightarrow p_{01} = 0.3848$ bar. $\frac{p_{02}}{p_1} = 8$

Compressor 01 – 02 $p_{02} = p_{01} \times 8 = 3.07$ bar.

$\eta_c = 0.85$

$T_{02} - T_{01} = \frac{T_{01}}{\eta_c}\left[\left(\frac{p_{02}}{p_{01}}\right)^{\frac{\gamma-1}{\gamma}} - 1\right] = 236$ K $T_{02} = 484$ K.

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Numerical Problems

Q1. Determine the specific thrust, fuel consumption for a simple turbojet engine with following specification: compressor pressure ratio: 8, turbine inlet temperature: 1250 K, Isentropic efficiency: intake (0.93), compressor (0.85), turbine (0.9), propelling nozzle (0.95), mechanical and combustion efficiency: 0.98, combustion chamber pressure loss: 4% of compressor delivery pressure, exhaust pressure loss: 0.03 bar, ambient condition: 0.26 bar, 220 K; Mach number: 0.8.

$c_{pg} = 1.148$ kJ/kg K
$c_{pa} = 1.005$ kJ/kg K

Turbine 03 - 04 $w_t = \frac{w_c}{\eta_m} = c_{pa}(T_{02} - T_{01})$ $\eta_m = 0.98$.

$c_{pg}(T_{03} - T_{04}) = \frac{c_p}{\eta_m}(T_{02} - T_{01}) \Rightarrow T_{03} - T_{04} = 210.8$ K.

$T_{03} = 1250$ K.

$\Rightarrow T_{04} = 1093.2$ K.

$p_{03} = p_{02}\left(1 - \frac{\Delta p_b}{p_{02}}\right) = 2.947$ bar. ($\frac{\Delta p_b}{p_{02}}$ = 4%)

$\eta_t = \frac{T_{03} - T_{04}}{T_{03} - T_{04}'} = 0.9 \Rightarrow T_{04}' = 1016$ K

$\gamma = 1.33$

$\frac{p_{04}}{p_{03}} = \left(\frac{T_{04}'}{T_{03}}\right)^{\frac{\gamma}{\gamma-1}} \Rightarrow p_{04} = 1.284$ bar

$NPR = \frac{p_{04}}{p_a} = \frac{1.284}{0.26} = 4.94$

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Numerical Problems

Q1. Determine the specific thrust, fuel consumption for a simple turbojet engine with following specification: compressor pressure ratio: 8, turbine inlet temperature: 1250 K, Isentropic efficiency: intake (0.93), compressor (0.85), turbine (0.9), propelling nozzle (0.95), mechanical and combustion efficiency: 0.98, combustion chamber pressure loss: 4% of compressor delivery pressure, exhaust pressure loss: 0.03 bar, ambient condition: 0.26 bar, 220 K; Mach number: 0.8.

$\eta_j = 0.95$
$\gamma = 1.33$.

Propelling Nozzle $\frac{p_{04}}{p_c} = \frac{1}{\left[1 - \frac{1}{\eta_j}\left(\frac{\gamma-1}{\gamma+1}\right)\right]^{\gamma/\gamma-1}} = 1.9$

$\frac{p_{04}}{p_a} = 4.94 > \frac{p_{04}}{p_c}$.

Nozzle is choking.

$T_5 = T_c = \left(\frac{2}{\gamma+1}\right) T_{04} = 892$ K.

$p_5 = p_c = p_{04}\left(\frac{1}{p_{04}/p_c}\right) = \frac{1.284}{1.9} = 0.675$ bar.

$R = 287$ J/kg K.

$\rho_5 = \frac{p_c}{R T_c} = 0.263$ kg/m3.

$C_5 = \sqrt{\gamma R T_c} = \sqrt{1.33 \times 287 \times 892} = 583.5$ m/s.

$m_5 = \rho_5 A_5 C_5$

$\frac{A_5}{m} = \frac{1}{\rho_5 C_5} = 0.0065$ m²s/kg.

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Numerical Problems

Q1. Determine the specific thrust, fuel consumption for a simple turbojet engine with following specification: compressor pressure ratio: 8, turbine inlet temperature: 1250 K, Isentropic efficiency: intake (0.93), compressor (0.85), turbine (0.9), propelling nozzle (0.95), mechanical and combustion efficiency: 0.98, combustion chamber pressure loss: 4% of compressor delivery pressure, exhaust pressure loss: 0.03 bar, ambient condition: 0.26 bar, 220 K; Mach number: 0.8.

Specific thrust $F_s = (C_5 - C_a) + \frac{A_5}{m}(p_c - p_a)$.

$= (583.5 - 238) + 0.0065\,(0.675 - 0.26) \times 10^5$

$F_s = 614.5$ N.S/kg.

$f_{th} = 0.022$

$SFC = \frac{3600 f_{act}}{F_s}$.

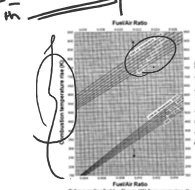
$SFC = 0.1315$ kg/hr.N

$T_{02} = 484$ K.

$\Delta T = T_{03} - T_{02} =$
$= 1250 - 484$
$= 766$ K.

$f_{act} = \frac{f_{th}}{\eta_c} = \frac{0.22}{0.9}$

$f_{ac} = 0.02244$



Reference: Gas Turbine Theory, HIH Saravanamuttoo, H. Cohen and GFC Rogers, Pearson, India, 2012

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THANK YOU

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