Jet Aircraft Propulsion

Prof. Bhaskar Roy, Prof. A M Pradeep
Department of Aerospace Engineering,
IIT Bombay

Lect-10

In this lecture...

- Real cycle analysis
  - Turbojet engine
  - Turbojet with afterburning
  - Turbofan engine
  - Turboprop and turboshaft engines

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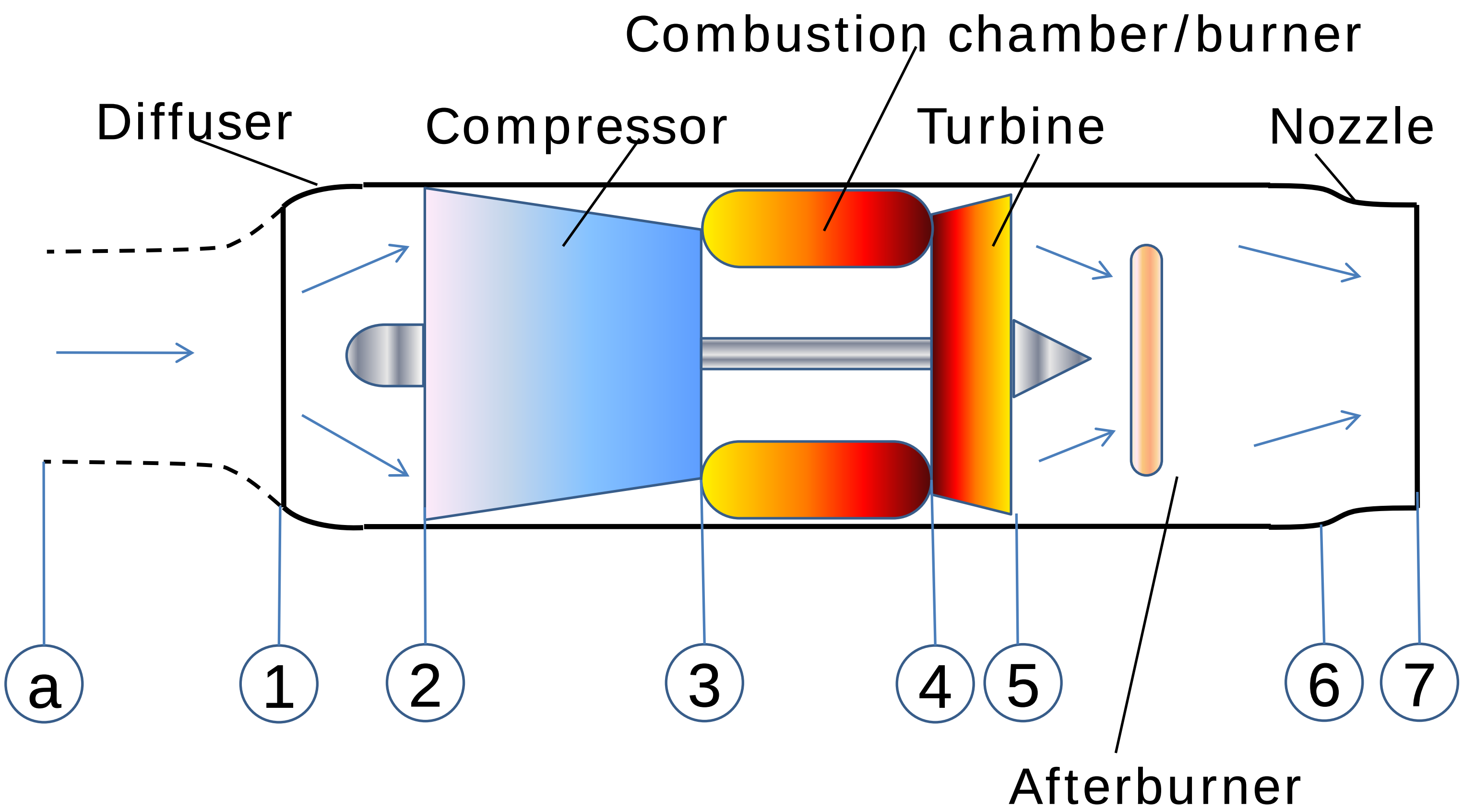
Real cycle for turbojet engines



Schematic of a turbojet engine and station numbering scheme

Real cycle for turbojet engines

- The different processes in a turbojet cycle are the following:
- a-1: Air from far upstream is brought to the air intake (diffuser) with some acceleration/deceleration
- 1-2: Air is decelerated as is passes through the diffuser
- 2-3: Air is compressed in a compressor (axial or centrifugal)
- 3-4 The air is heated using a combustion chamber/burner

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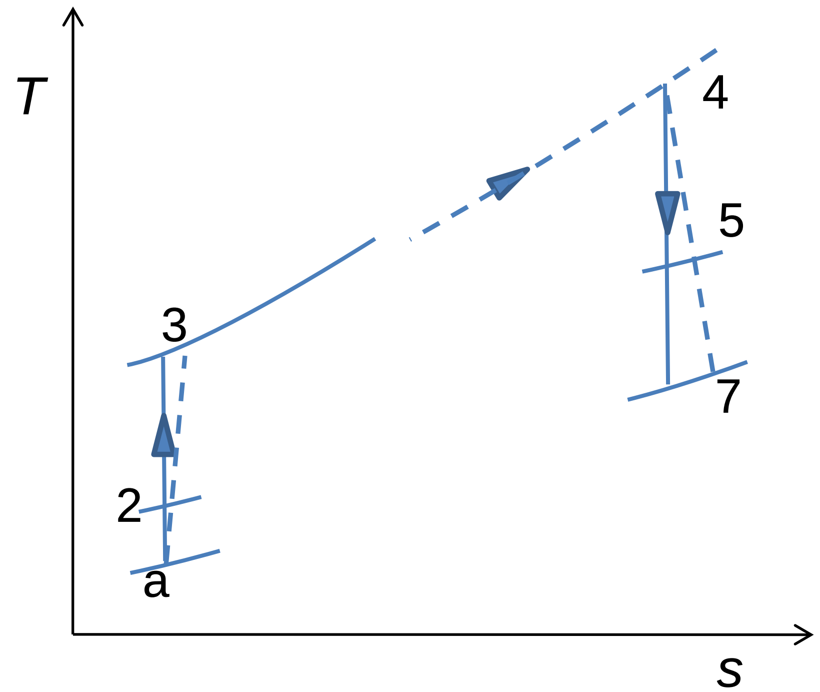
Real cycle for turbojet engines

- 4-5: The air is expanded in a turbine to obtain power to drive the compressor
- 5-6: The air may or may not be further heated in an afterburner by adding further fuel
- 6-7: The air is accelerated and exhausted through the nozzle.

Real cycle for turbojet engines



Real turbojet cycle (without afterburning) on a T-s diagram

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Real cycle for turbojet engines

- For cycle analysis we shall take up each component and determine the exit conditions based on known inlet parameters.
- Intake: Ambient pressure, temperature and Mach number are known, P_a, T_a and M

$$T_{02} = T_a\left(1+\frac{\gamma-1}{2}M^2\right)$$

$$\eta_d = \frac{T_{02}-T_a}{T_{02s}-T_a} = \frac{T_{02}/T_a-1}{T_{02s}/T_a-1} = \frac{T_{02}/T_a-1}{(P_{02}/P_a)^{(\gamma-1)/\gamma}-1}$$

$$\therefore \quad P_{02} = P_a\left(1+\eta_d\left(\frac{T_{02}}{T_a}-1\right)\right)^{\gamma/(\gamma-1)}$$

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Real cycle for turbojet engines

- Compressor: Let the known compressor pressure ratio be denoted as π_c

Compressor exit pressure is

$$P_{03} = \pi_c P_{02}$$

We know that the compressor efficiency is

$$\eta_C = \frac{T_{03s} - T_{02}}{T_{03} - T_{02}} = \frac{T_{03s}/T_{02} - 1}{T_{03}/T_{02} - 1} = \frac{\pi_c^{(\gamma-1)/\gamma} - 1}{T_{03}/T_{02} - 1}$$

Simplifying,

$$T_{03} = T_{02}\left\{\frac{1}{\eta_C}\left[\pi_c^{(\gamma-1)/\gamma} - 1\right] + 1\right\}$$

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Real cycle for turbojet engines

- Combustion chamber: From energy balance,

$$h_{04} = h_{03} + \eta_b f \dot{Q}_f$$

$$c_{pg} T_{04} = c_{pa} T_{03} + \eta_b f \dot{Q}_f$$

$$or,\ f = \frac{c_{pg} T_{04} / c_{pa} T_{03} - 1}{\eta_b \dot{Q}_f / c_{pa} T_{03} - c_{pg} T_{04} / c_{pa} T_{03}}$$

$$\text{Also, } P_{04} = \pi_b P_{03}$$

- Hence, we can determine the fuel to air ratio and the combustion chamber exit total pressure.

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Real cycle for turbojet engines

- Turbine: Since the turbine produces work to drive the compressor, $W_{turbine} = W_{compressor}$

$$\eta_m(\dot{m}+\dot{m}_f)c_{pg}(T_{04}-T_{05}) = \dot{m}c_{pa}(T_{03}-T_{02})$$

$$T_{05} = c_{pg}T_{04} - c_{pa}(T_{03}-T_{02})/\eta_m(1+f)$$

$$\eta_t = \frac{T_{04}-T_{05}}{T_{04}-T_{05s}} = \frac{1-T_{05}/T_{04}}{1-T_{05s}/T_{04}} = \frac{1-T_{05}/T_{04}}{1-(P_{05}/P_{04})^{(\gamma-1)/\gamma}}$$

Simplifying,

$$P_{05} = P_{04}\left[1-\frac{1}{\eta_t}(1-T_{05}/T_{04})\right]^{\gamma/(\gamma-1)}$$

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Real cycle for turbojet engines

- Nozzle: With no afterburner, $T_{06}=T_{05}$, $P_{06}=\pi_{AB}P_{05}$

Therefore, the nozzle exit kinetic energy,

$$\frac{u_e^2}{2} = h_{07} - h_7 = \eta_n (h_{07} - h_{7s})$$

Since, $h_{07} = h_{06}$

$$u_e = \sqrt{2c_p \eta_n T_{06}\left[1 - \left(P_a / P_{06}\right)^{(\gamma-1)/\gamma}\right]}$$

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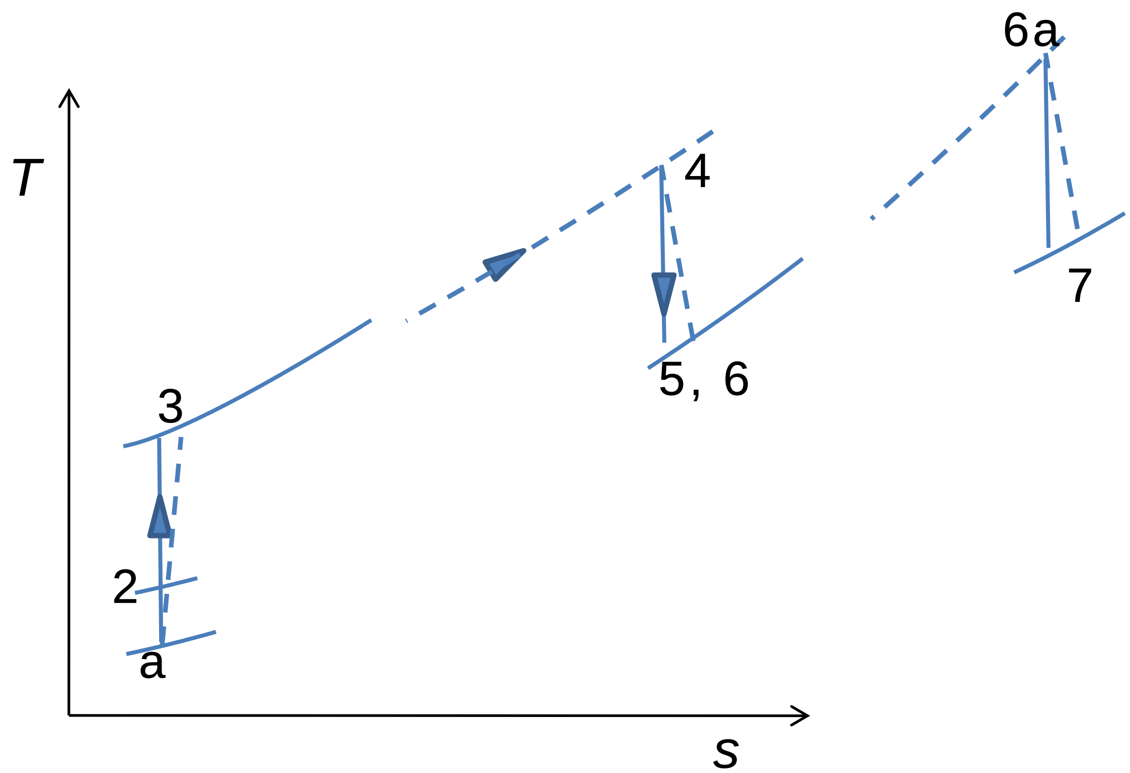
Real cycle for turbojet engines



Real turbojet cycle (with afterburning) on a T-s diagram

Real cycle for turbojet engines

- Afterburning: used when the aircraft needs a substantial increment in thrust. For eg. to accelerate to and cruise at supersonic speeds.
- Since the air-fuel ratio in gas turbine engines are much greater than the stoichiometric values, there is sufficient amount of air available for combustion at the turbine exit.
- There are no rotating components like a turbine in the afterburner, the temperatures can be taken to much higher values than that at turbine entry.

Real cycle for turbojet engines

- For calculating the fuel flow rate required to achieve a temperature of T_{6a}, we carry out an energy balance similar to that of the combustor.
- The total fuel flow rate, f, is equal to the sum of the fuel flow rates in the main combustor and the afterburner.

$$f = f_1 + f_2$$

- Where f_1 is the fuel flow rate in the main combustor and f_2, the fuel flow rate in the afterburner.

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Real cycle for turbofan engines

- A turbofan engine can have different configurations: Twin-spool, three-spool, and geared turbofan. These may be either unmixed or mixed.
- Cycle analysis of a turbofan can hence be slightly different depending upon the configuration of the engine.
- We shall now carry out an real cycle analysis of an unmixed twin-spool turbofan engine.

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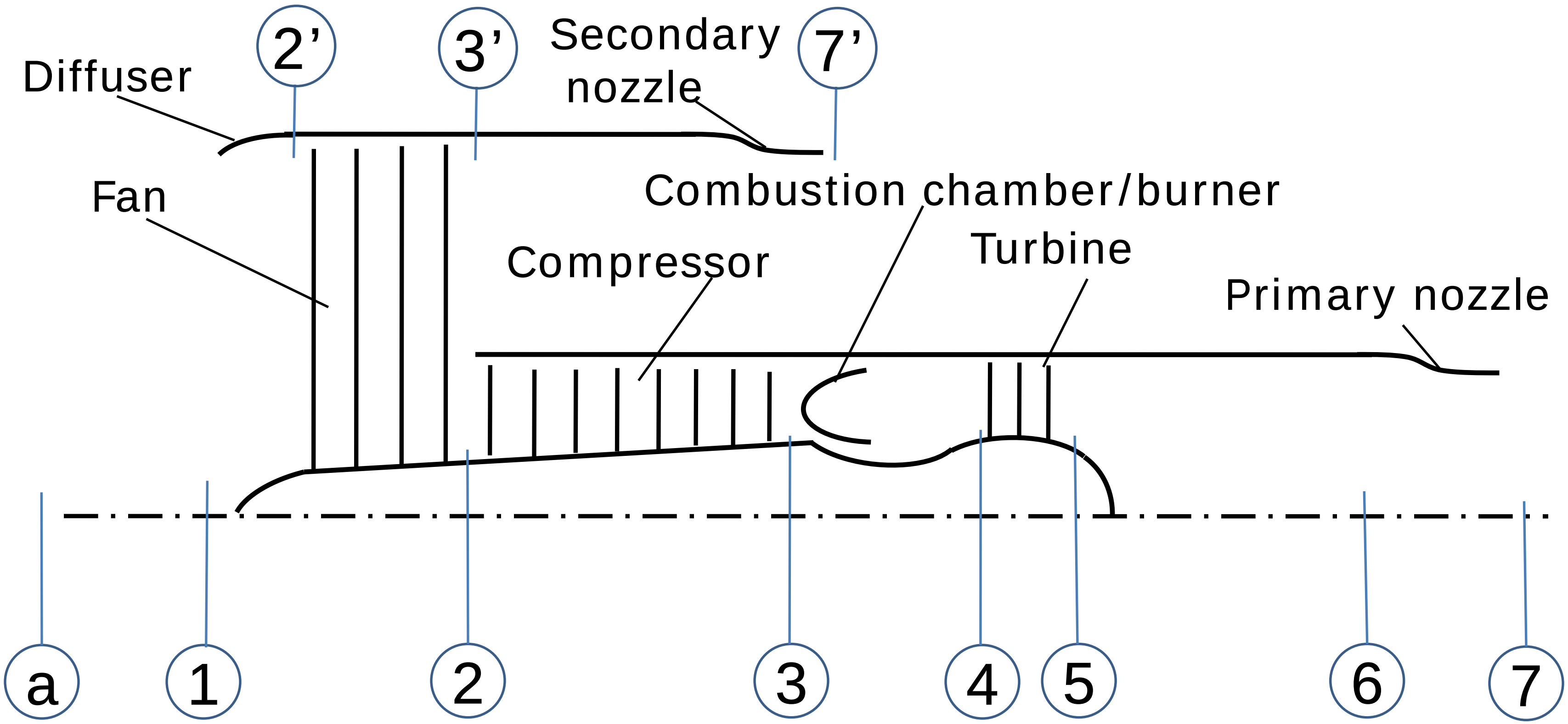
Real cycle for turbofan engines



Schematic of an unmixed turbofan engine and station numbering scheme

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Real cycle for turbofan engines

- Intake: Ambient pressure, temperature and Mach number are known, P_a, T_a and M
- Intake exit stagnation temperature and pressure are determined from the isentropic relations:

$$T_{02'} = T_a\left(1+\frac{\gamma-1}{2}M^2\right)$$

$$\eta_d = \frac{T_{02'}-T_a}{T_{02's}-T_a} = \frac{T_{02'}/T_a-1}{T_{02's}/T_a-1} = \frac{T_{02'}/T_a-1}{(P_{02'}/P_a)^{(\gamma-1)/\gamma}-1}$$

$$\therefore \quad P_{02'} = P_a\left(1+\eta_d\left(\frac{T_{02'}}{T_a}-1\right)\right)^{\gamma/(\gamma-1)}$$

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Real cycle for turbofan engines

- Fan: Fan pressure ratio is known, $\pi_f = P_{03'} / P_{02'}$

$$P_{03'} = \pi_f P_{02'}$$

$$T_{03'} = T_{02'} \left(\pi_f\right)^{(\gamma-1)/\gamma}$$

The fan efficiency is

$$\eta_f = \frac{T_{03's} - T_{02'}}{T_{03'} - T_{02'}} = \frac{T_{03's} / T_{02'} - 1}{T_{03'} / T_{02'} - 1} = \frac{\pi_f^{(\gamma-1)/\gamma} - 1}{T_{03'} / T_{02'} - 1}$$

Simplifying,

$$T_{03'} = T_{02'} \left\{ \frac{1}{\eta_f} \left[\pi_f^{(\gamma-1)/\gamma} - 1 \right] + 1 \right\}$$

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Real cycle for turbofan engines

- Compressor: The compressor inlet total pressure, P_{02} = fan outlet total pressure, $P_{03'}$
- The compressor inlet total temperature is equal to the fan outlet total temperature.
- The compressor exit conditions can be determined in a manner exactly the same as discussed for the turbojet.
- Similarly, the combustion chamber exit conditions can also be determined.

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Real cycle for turbofan engines

- Turbine: There are several configurations possible for a turbofan.
- Let us assume that the engine has two spools.
- The fan driven by the low pressure turbine (LPT).
- The compressor is driven by the high pressure turbine (HPT).
- The work done by the LPT should be equal to the fan work and the work done by the HPT should be equal to the compressor work.

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Real cycle for turbofan engines

- High pressure turbine:

$$\eta_m(\dot{m}+\dot{m}_H)c_{pg}(T_{04}-T_{05'})=\dot{m}_H c_{pa}(T_{03}-T_{02})$$

Here, $T_{05'}$ is the temperature at the HPT exit.

$$T_{05'}=c_{pg}T_{04}-c_{pa}(T_{03}-T_{02})/c_{pg}\eta_m(1+f)$$

$$\text{Hence, } P_{05'}=P_{04}\left[1-\frac{1}{\eta_t}(1-T_{05'}/T_{04})\right]^{\gamma/(\gamma-1)}$$

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Real cycle for turbofan engines

- Low pressure turbine:

$$\eta_m(\dot{m}+\dot{m}_C)c_{pg}(T_{05'}-T_{05})=\dot{m}_C c_{pa}(T_{03'}-T_{02'})$$

Here, $T_{05'}$ is the temperature at the HPT exit/LPT inlet.

$$\therefore\ \eta_m(1+f)c_{pg}(T_{05'}-T_{05})=\mathrm{B}c_{pa}(T_{03'}-T_{02'}),\ \text{where, } \mathrm{B}=\frac{\dot{m}_C}{\dot{m}_H}$$

$$T_{05}=c_{pg}T_{05'}-\mathrm{B}c_{pa}(T_{03'}-T_{02'})/\eta_m c_{pg}(1+f)$$

$$\text{And, } P_{05}=P_{05'}\left[1-\frac{1}{\eta_t}(1-T_{05}/T_{05'})\right]^{\gamma/(\gamma-1)}$$

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Real cycle for turbofan engines

- The total thrust developed by the turbofan with two separate unmixed streams will consist of thrust due to primary nozzle and that due to the secondary nozzle.
- Fn= Fn(primary nozzle) + Fn (secondary nozzle)

$$F_n = \dot{m}_H \left[(1+f)V_{ex} - V\right] + \mathrm{B}\dot{m}_H (V_{exf} - V)$$

assuming $(P_e - P_a)A_e$ to be negligible.

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Real cycle for turbofan engines

- The cycle analysis procedure will need to be slightly modified depending upon the turbofan engine configuration.
- The differences in the various configuration arise because of the number of spools and turbine-compressor/fan arrangements as well as mixed and unmixed exhausts.
- If the turbofan is of a mixed configuration, then, we will have to calculate the temperature at the nozzle entry from enthalpy balance of the two streams.

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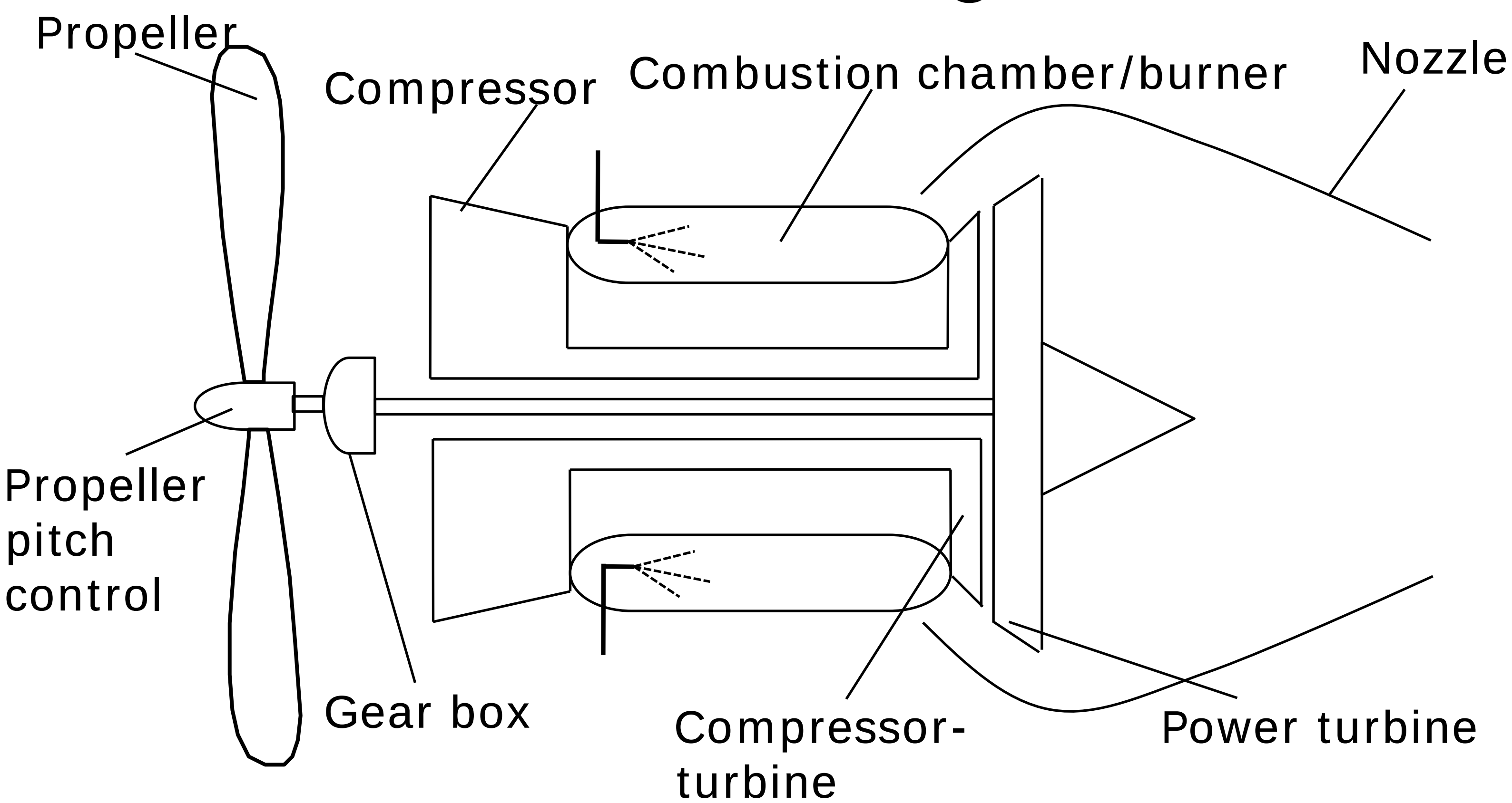
Real cycle for turboprop and turboshaft engines

- The cycle analysis procedure will need to be slightly modified depending upon the turbofan engine configuration.
- The differences in the various configuration arise because of the number of spools and turbine-compressor/fan arrangements as well as mixed and unmixed exhausts.
- If the turbofan is of a mixed configuration, then, we will have to calculate the temperature at the nozzle entry from enthalpy balance of the two streams.

Real cycle for turboprop and turboshaft engines



Schematic of typical turboprop engine

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Real cycle for turboprop and turboshaft engines

- Turboprops and turboshafts usually have a free-turbine or power turbine to drive the propeller or the main rotor blade (turboshafts).
- Stress limitations require that the large diameter propeller rotate at a much lower rate and hence a speed reducer is required.
- Turboprops may also have a thrust component due to the jet exhaust in addition to the propeller thrust.
- In turboshafts, however, there is no thrust component due to the nozzle.

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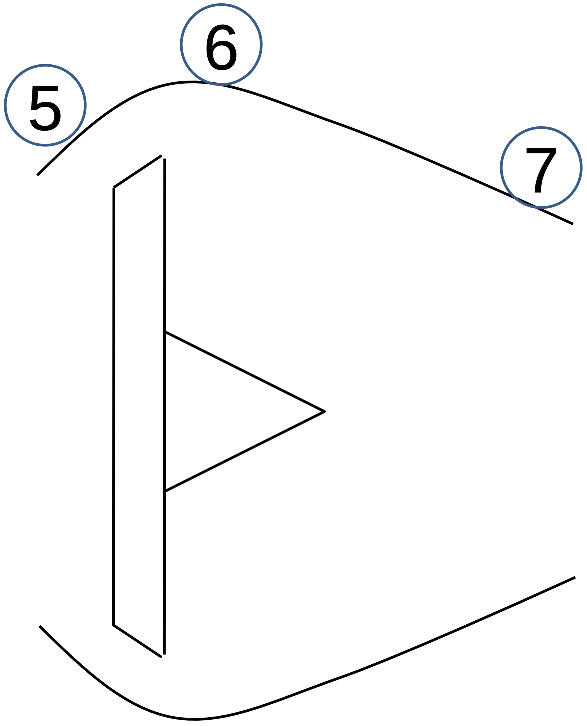
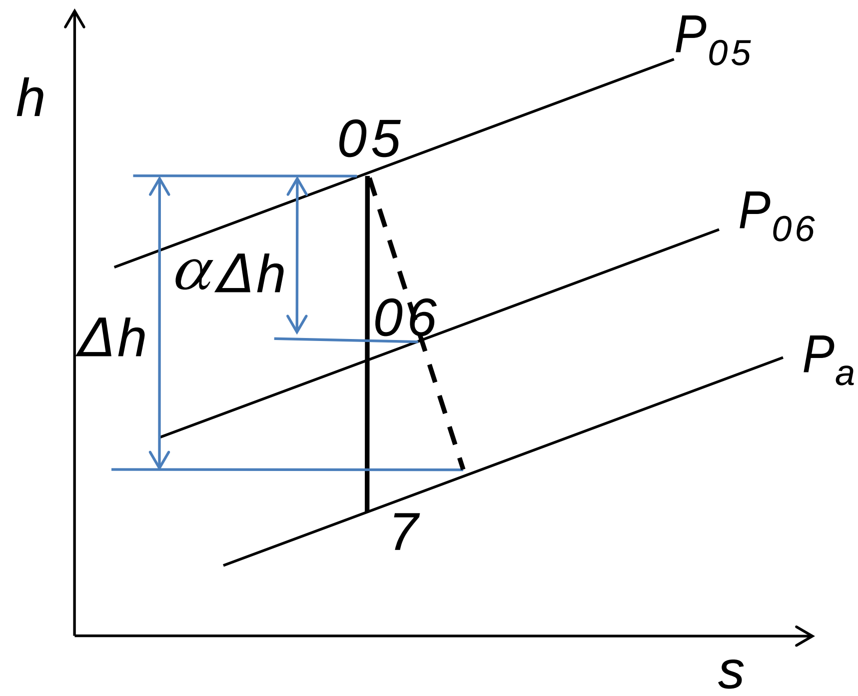
Real cycle for turboprop and turboshaft engines





Enthalpy-entropy diagram for power turbine-exhaust nozzle analysis

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Real cycle for turboprop and turboshaft engines

- Δh is the enthalpy drop in an ideal isentropic power turbine and exhaust nozzle.
- α is the fraction of Δh that would be used by an isentropic turbine.
- The propeller thrust power, $F_{n,pr}V$, is

$$F_{n,pr}V = \eta_{pr}\eta_g\eta_{PT}\alpha\,\Delta h\,\dot{m} \quad \text{or, } F_{n,pr} = \frac{\eta_{pr}\eta_g\eta_{PT}\alpha\,\Delta h\,\dot{m}}{V}$$

$$\eta_{pr} = \text{propeller efficiency}, \eta_g = \text{gear box efficiency},$$

$$\eta_{PT} = \text{power turbine efficiency}$$

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Real cycle for turboprop and turboshaft engines

- The exhaust nozzle thrust, F_n ,

$$F_n = \dot{m}(V_{ex} - V),\ \text{where,}\ V_{ex} = \sqrt{2(1-\alpha)\eta_n \Delta h}$$

- Thus, the total thrust is given by,

$$F = F_{n,pr} + F_n = \frac{\eta_{pr}\eta_g \eta_{PT} \alpha \, \Delta h \, \dot{m}}{V} + \dot{m}(\sqrt{2(1-\alpha)\eta_n \Delta h} - V)$$

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In the next lecture…

- Tutorial
  - Solve problems involving real cycle analysis

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