Introduction to Aerospace Propulsion

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Lecture No - 33

In this lecture ...

- Ideal cycle for jet engines
  - Turbofan engine
  - Different configurations of turbofan engines
  - Turboprop and Turboshaft engines
  - Ramjets

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Turbofan engine

- Propulsion efficiency is a function of the exhaust velocity to flight speed ratio.
- This can be increased by reducing the effective exhaust velocity.
- In a turbofan engine, a fan of a larger diameter than the compressor is used to generate a mass flow higher than the core mass flow.
- This ratio $\left(\dot{m}_{cold} / \dot{m}_{hot}\right)$ is called the bypass ratio.
- Turbofan engines have a higher propulsion efficiency as compared with turbojet engines operating in the same speed range.

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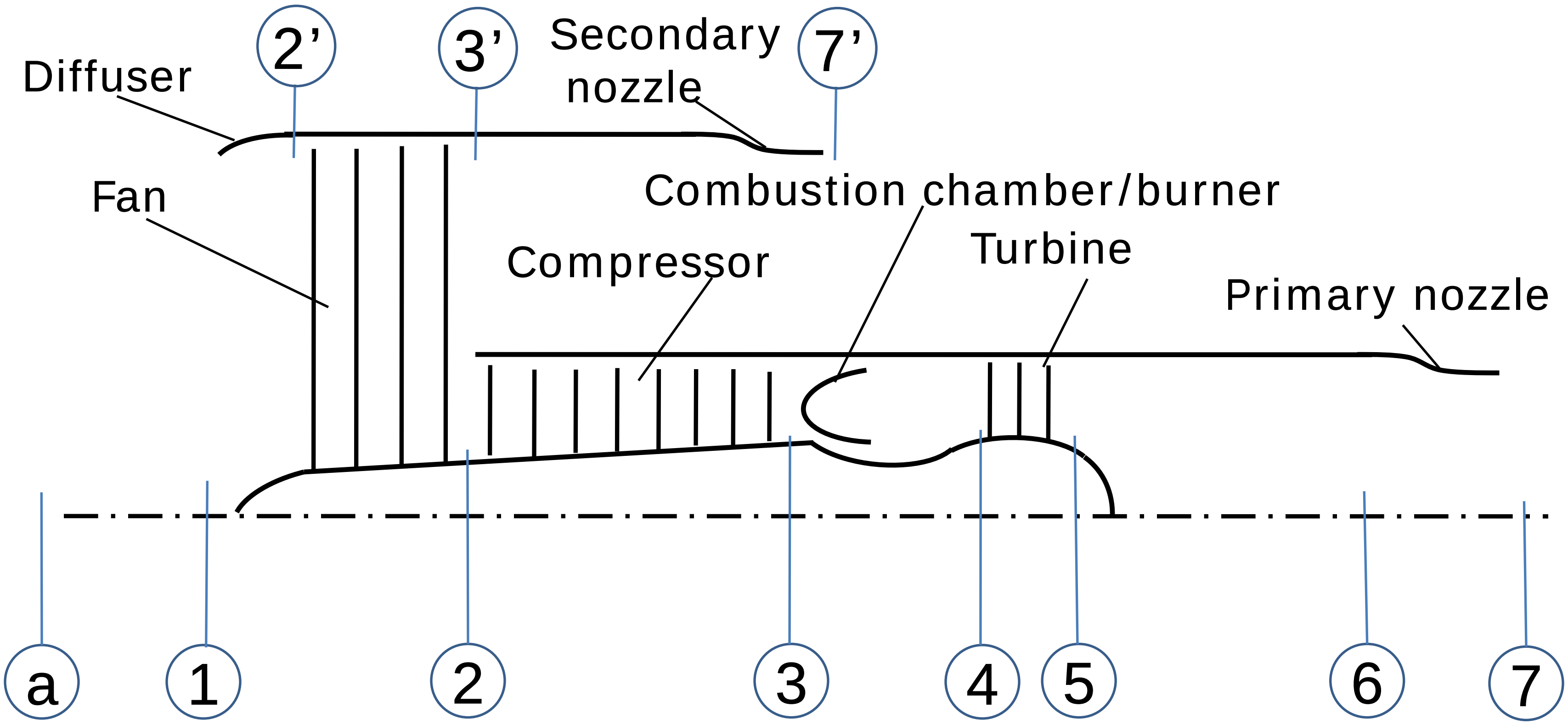
Ideal turbofan engine



Schematic of an unmixed turbofan engine and station numbering scheme

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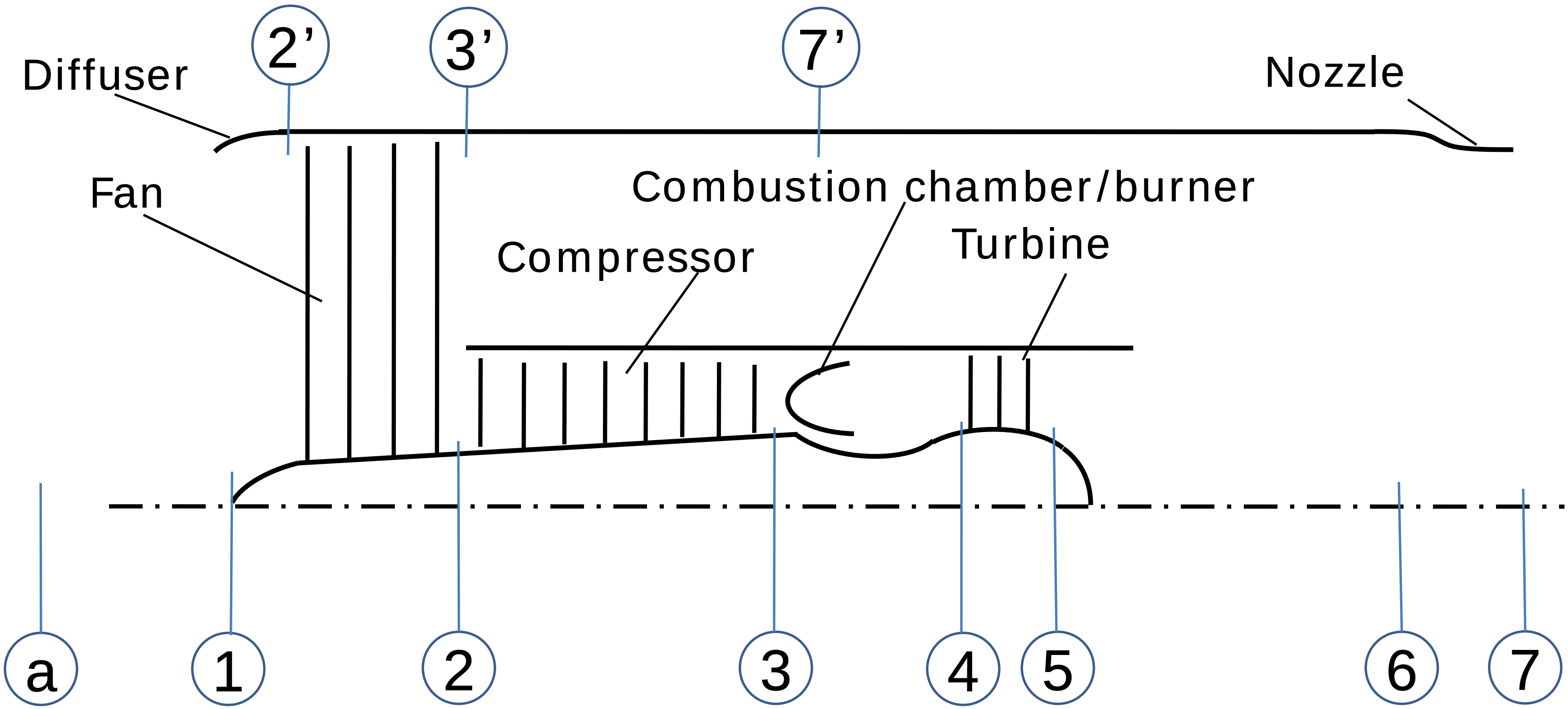
Ideal turbofan engine



Schematic of a mixed turbofan engine and station numbering scheme

Ideal turbofan engine

- The different processes in an unmixed turbofan 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 fan
- 2-3: Air is compressed in a compressor (axial or centrifugal)

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Ideal turbofan engine

- 3-4 The air is heated using a combustion chamber/burner
- 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 primary nozzle.
- 3'-7': The air in the bypass duct is accelerated and expanded through the secondary nozzle.

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Ideal turbofan engine

- 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 ideal cycle analysis of an unmixed twin-spool turbofan engine.
- Subsequently we shall also discuss the mixed version of the engine.

Ideal turbofan engine

- 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:

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

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

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

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

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

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Ideal turbofan engine

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

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

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

- Combustion chamber: From energy balance,

$$h_{04} = h_{03} + fQ_R$$

$$or,\ f = \frac{T_{04}/T_{03} - 1}{Q_R/c_p T_{03} - T_{04}/T_{03}}$$

- Hence, we can determine the fuel-air ratio.

Ideal 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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Ideal turbofan engines

- High pressure turbine:

$$\dot{m}_t c_p (T_{04} - T_{05'}) = \dot{m}_{aH} c_p (T_{03} - T_{02})$$

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

$$\therefore (1+f)(T_{04} - T_{05'}) = (T_{03} - T_{02})$$

$$T_{05'} = T_{04} - (T_{03} - T_{02})/(1+f)$$

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

For an ideal combustion chamber, $P_{04} = P_{03}$

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Ideal turbofan engines

- Low pressure turbine:

$$\dot{m}_t c_p (T_{05'} - T_{05}) = \dot{m}_{aC} c_p (T_{03'} - T_{02'})$$

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

$$\therefore (1+f)(T_{05'} - T_{05}) = \mathrm{B}(T_{03'} - T_{02'}), \text{ where, } \mathrm{B} = \frac{\dot{m}_{aC}}{\dot{m}_{aH}}$$

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

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

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Ideal turbofan engines

- Primary nozzle: With no afterburner, $T_{06}=T_{05}$, $P_{06}=P_{05}$

Therefore, the nozzle exit kinetic energy,

$$\frac{u_e^2}{2}=h_{07}-h_7$$

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

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

- This is similar to what we had derived for a pure turbojet.

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Ideal turbofan engines

- Secondary nozzle:

The secondary nozzle exit kinetic energy,

$$\frac{u_{ef}^2}{2} = h_{07'} - h_{7'}$$

Since, $h_{07'} = h_{03'}$

$$u_{ef} = \sqrt{2c_p T_{03'}\left[1 - \left(P_a / P_{03'}\right)^{(\gamma-1)/\gamma}\right]}$$

- The thrust and other parameters can now be calculated.

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Ideal turbofan engines

- Thrust,

$$\Im = \dot{m}_{aH}\left[(1+f)u_e - u\right] + B\dot{m}_{aH}(u_{ef} - u)$$

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

- SFC, TSFC, efficiencies can be calculated the same way as done for the turbojet case.

- 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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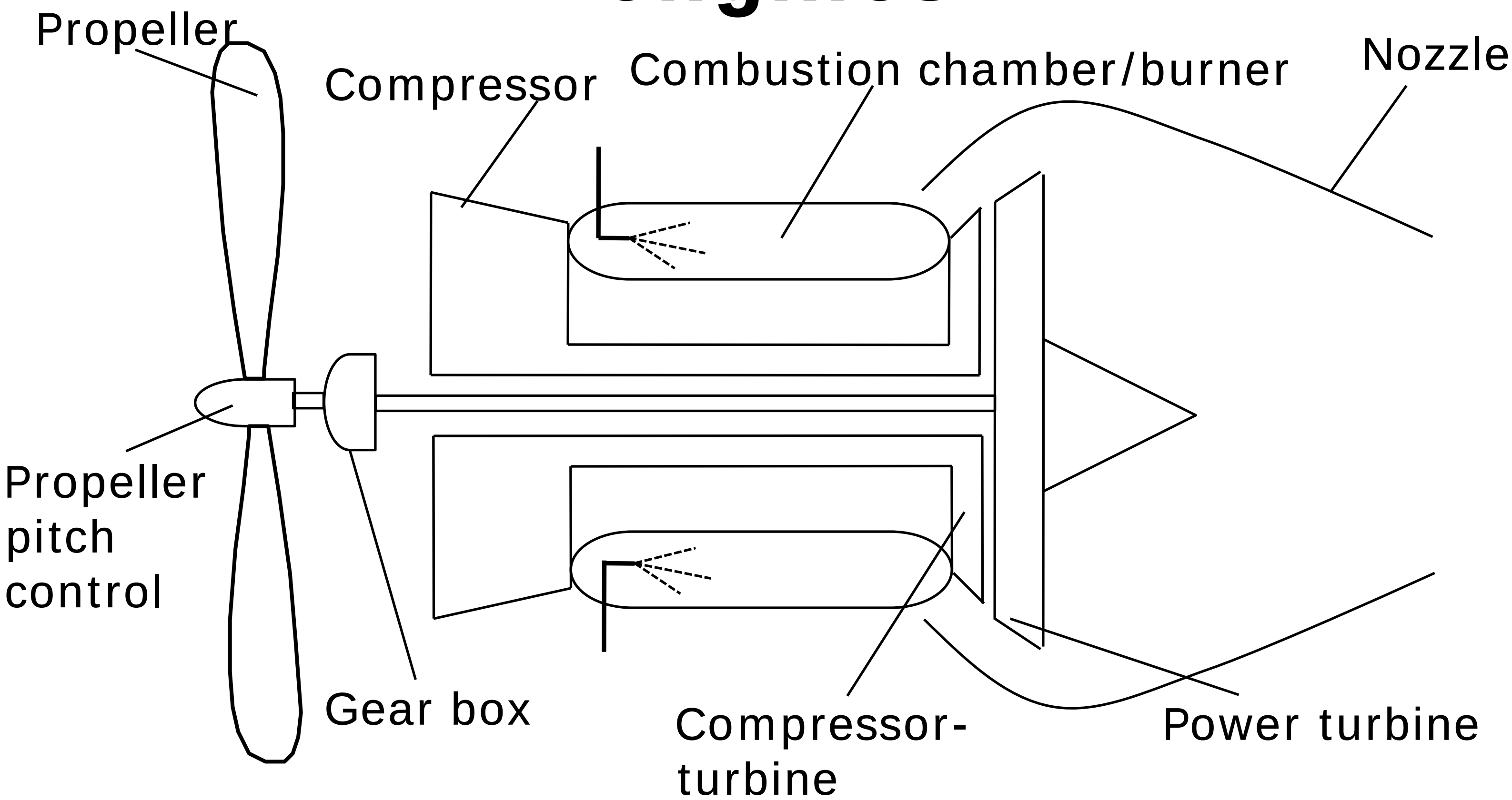
Ideal turbofan engines

- 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.
- Exercise: Carry out the ideal cycle analysis for a turbofan with three spool configuration with LPT driving the fan, Intermediate pressure turbine (IPT) driving the LPC and the HPT driving the HPC for mixed and unmixed configurations.

Ideal turboprop and turboshaft engines

- Turboprop engines generate a substantial shaft power in addition to nozzle thrust.
- Turboshaft engines, generate only shaft power. These engines are used in helicopters. The shaft power is used to drive the main rotor blade.
- In a turboprop engine, the advantages and limitations are those of the propeller.
- Both turboprops and turboshafts have applications at relatively lower speeds.

Ideal turboprop and turboshaft engines



Schematic of typical turboprop engine

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Ideal 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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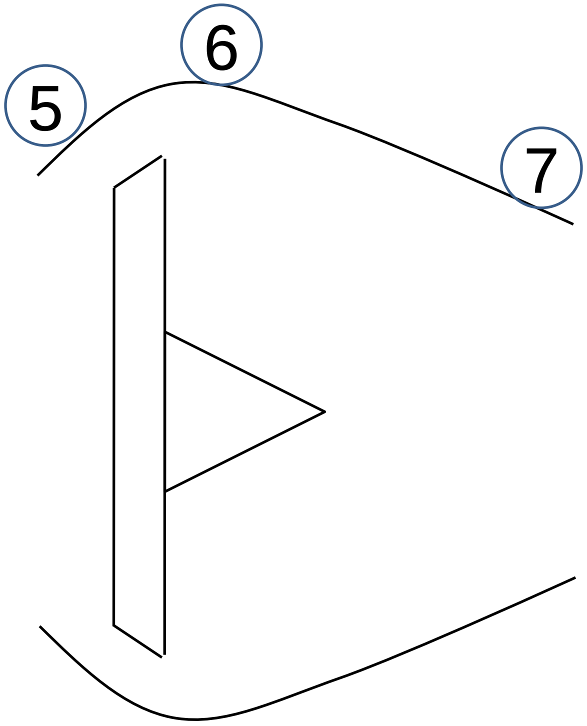
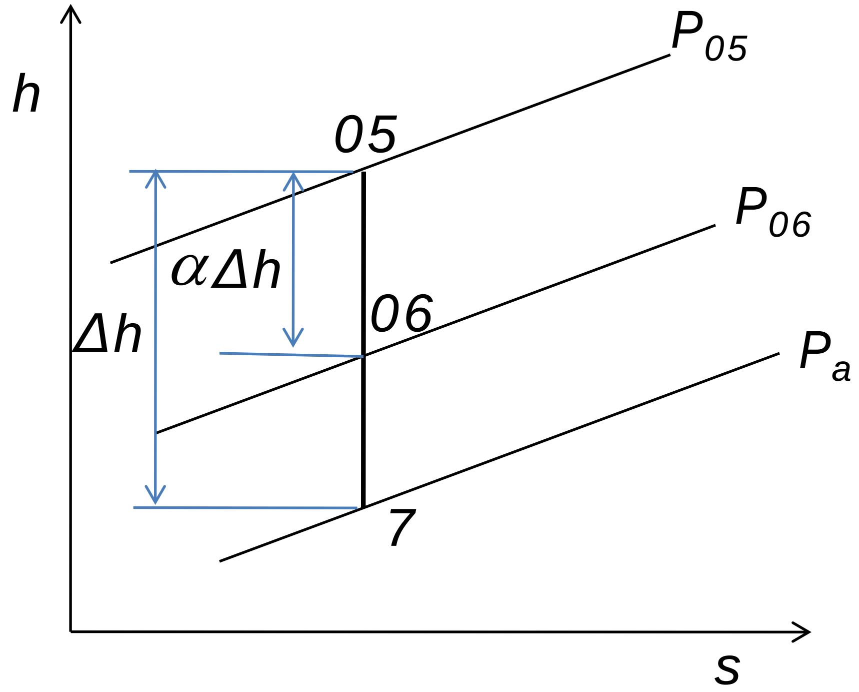
Ideal turboprop and turboshaft engines

- Cycle analysis for a turboshaft is similar to what was discussed for turbojets. The power output is only the shaft power and there is no thrust generated by the nozzle.
- In turboprops, thrust consists of two components, the propeller thrust and the nozzle thrust.
- The total thrust of a propeller is equal to the sum of the nozzle thrust and the propeller thrust.

Ideal turboprop and turboshaft engines





Enthalpy-entropy diagram for power turbine-exhaust nozzle analysis

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Ideal 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, $\Im_{pr}u$, is

$$\Im_{pr}u = \alpha \Delta h \dot{m} \quad \text{or,} \ \Im_{pr} = \frac{\alpha \Delta h \dot{m}}{u}$$

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Ideal turboprop and turboshaft engines

- The exhaust nozzle thrust, $\Im_n$,

$$\Im_n = \dot{m}(u_e - u), \text{ where, } u_e = \sqrt{2(1-\alpha)\Delta h}$$

- Thus, the total thrust is given by,

$$\Im = \Im_{pr} + \Im_n = \frac{\alpha\,\Delta h\,\dot{m}}{u} + \dot{m}(\sqrt{2(1-\alpha)\Delta h} - u)$$

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Ideal ramjet engines

- Ramjet is the simplest of all the airbreathing engines.
- It consists of a diffuser, combustion chamber and a nozzle.
- Ramjets are most efficient when operated at supersonic speeds.
- When air is decelerated from a high Mach number to a low subsonic Mach number, it results in substantial increase in pressure and temperature.
- Hence Ramjets do not need compressors and consequently no turbines as well.

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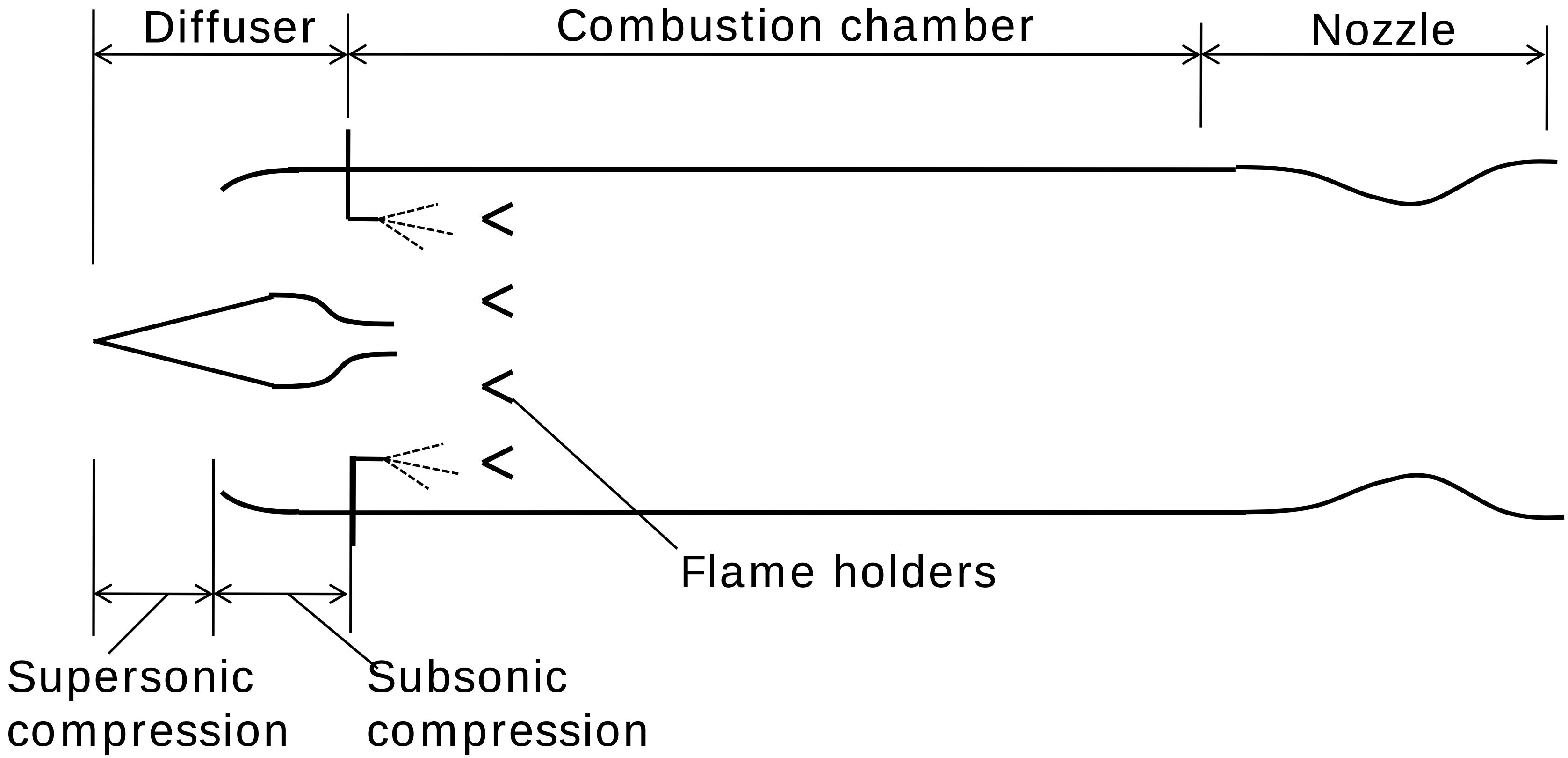
Ideal ramjet engines



Schematic of typical ramjet engine

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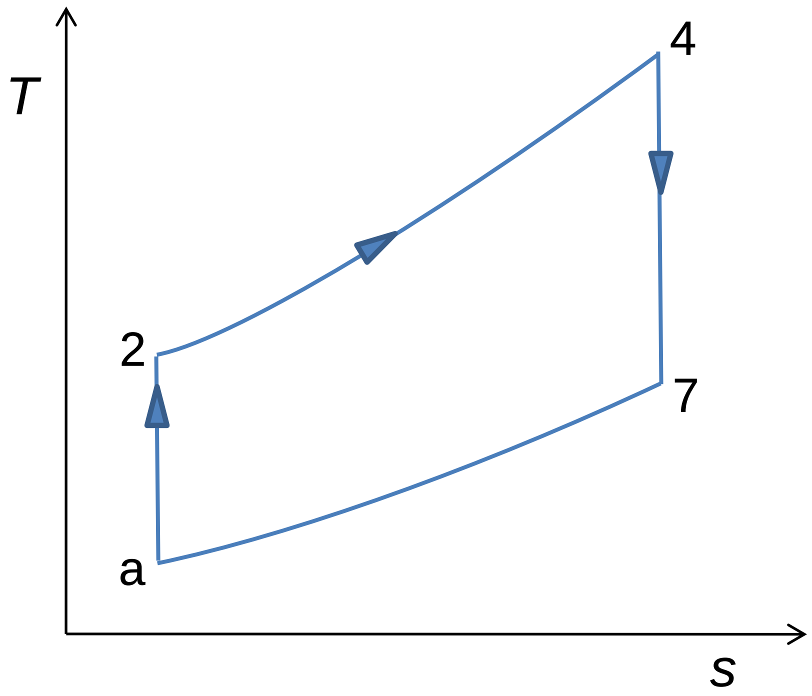
Ideal ramjet engines



a-2: isentropic compression in the intake
2-4: combustion at constant pressure
4-7: Isentropic expansion through the nozzle

Ideal ramjet cycle on a T-s diagram

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Ideal ramjet engines

- The ideal cycle analysis for a ramjet can be carried out in a manner that was discussed for turbojet engines.
- In a ramjet, there are no compressors and turbines and hence the analysis is simpler.
- Since ramjets depend upon the ram compression without the use of compressors, ramjets cannot generate static thrust.
- Therefore ramjets have to be taken to a sufficiently high speed at which ramjets can start generating thrust of its own.

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In the next lecture ...

- Solve problems
  - Ideal cycle analysis of air breathing engines

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