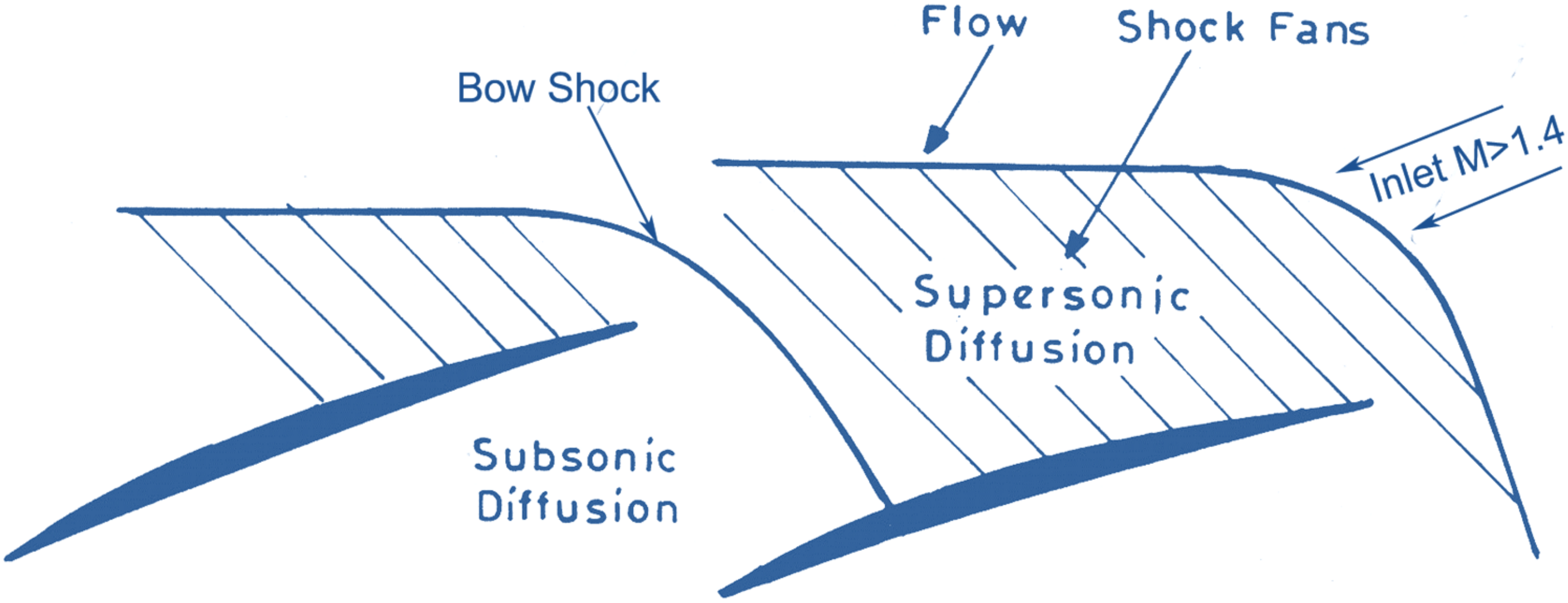
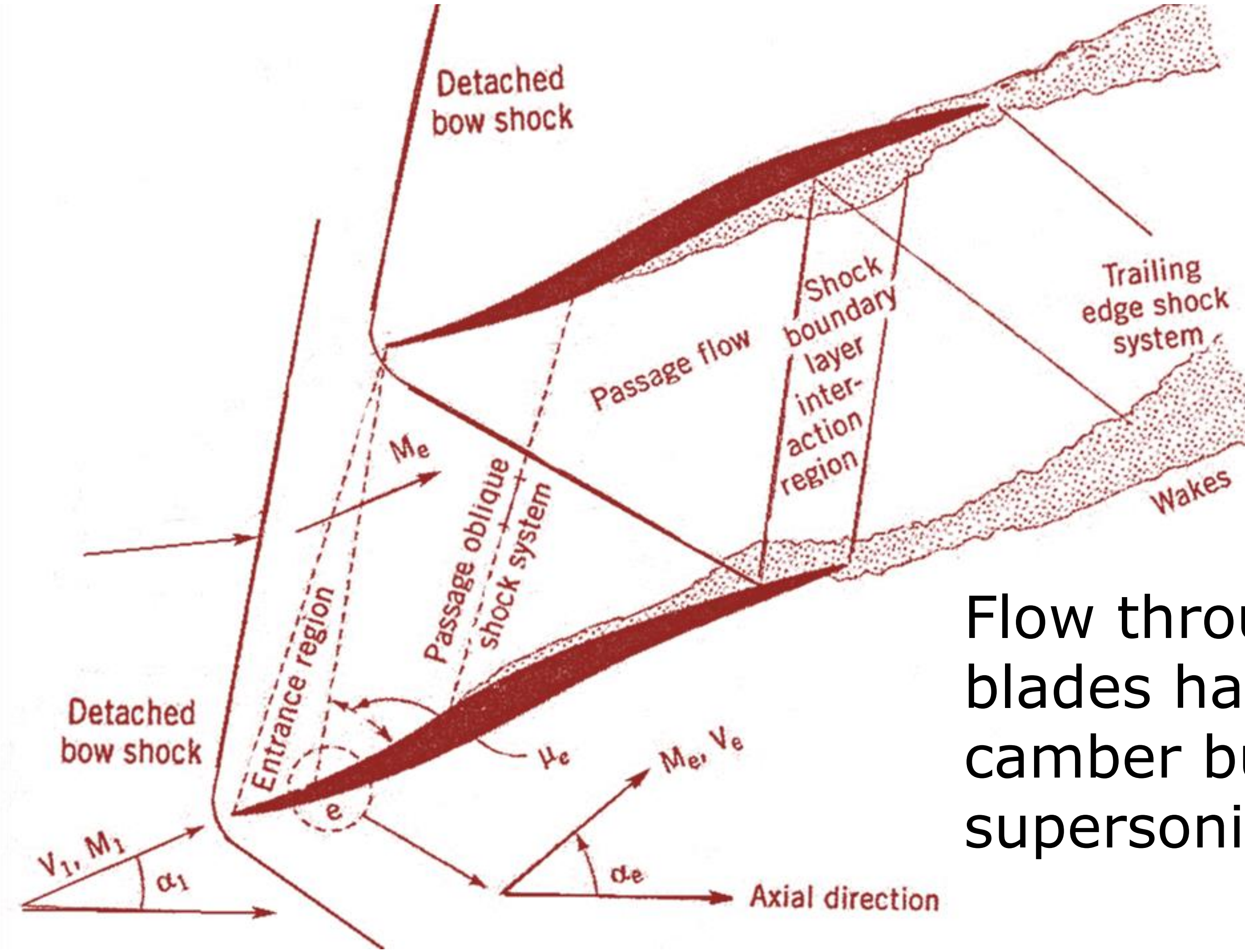
- Recap: Lecture 15: 18th September 2015, 1530-1655 hrs.
  - Transonic compressors
    - Mechanism of pressure rise
    - Types of transonic blades

Shocks in MCA blades





Flow through S-type blades has minimal camber but high supersonic diffusion

Transonic compressor cascade at M= 1.25

Source: http://www.dlr.de

Fan blade with a part-span snubber

Transonic blade with highly 3D shape

Axial flow turbines

Introduction

Gas Turbine engine derives its name from the turbine, which is at the heart of the work producing mechanism of the engine.

Principle

A fluid with large kinetic energy content is allowed to hit a freely rotating set of blades, certain amount of energy can be extracted from the passing fluid as shaft power.

Axial flow turbines

Cost of typical critical parts

- Cost of the exotic single-crystal turbine blade material is $75-125 per Kg.
- Cost of a new Single Crystal Commercial airline engine HP Turbine blade: $5,000 to 6,500
- Cost of a new Low Pressure aircraft turbine blade: $3,500
- Cost of a 100 MW power generation stage 1 new turbine blade: $13-15K
- Repair costs = 25-40% of cost of new blade

Axial flow turbines

- Axial turbines like axial compressors usually consists of one or more stages.
- The flow is accelerated in a nozzle/stator and then passes through a rotor.
- In the rotor, the working fluid imparts its momentum on to the rotor, that converts the kinetic energy to power output.
- Depending upon the power requirement, this process is repeated in multiple stages.

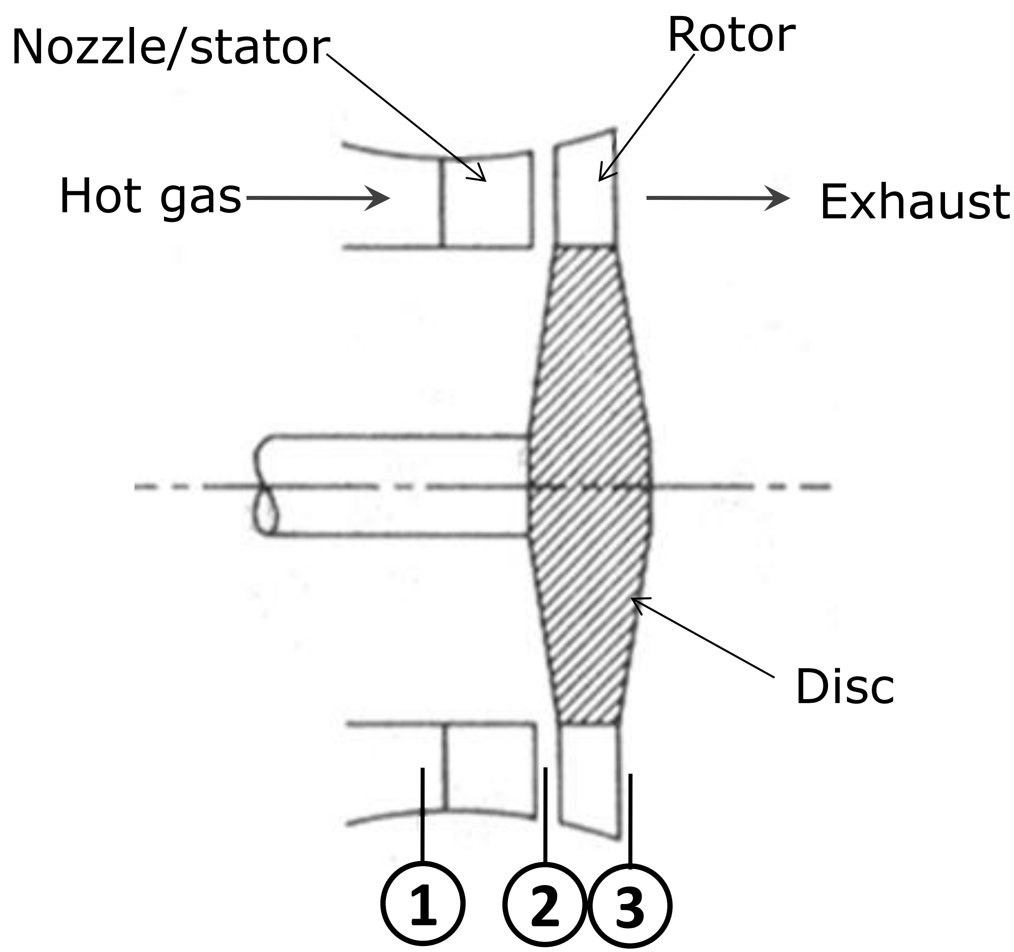
Axial flow turbines

- Due to motion of the rotor blades→ two distinct velocity components: absolute and relative velocities in the rotor.
- This is very much the case in axial compressors that was discussed earlier.
- Since turbines operate with a favourable pressure gradient, it is possible to have much higher pressure drop per stage as compared with compressors.
- Therefore, a single turbine stage can drive several stages of an axial compressor.

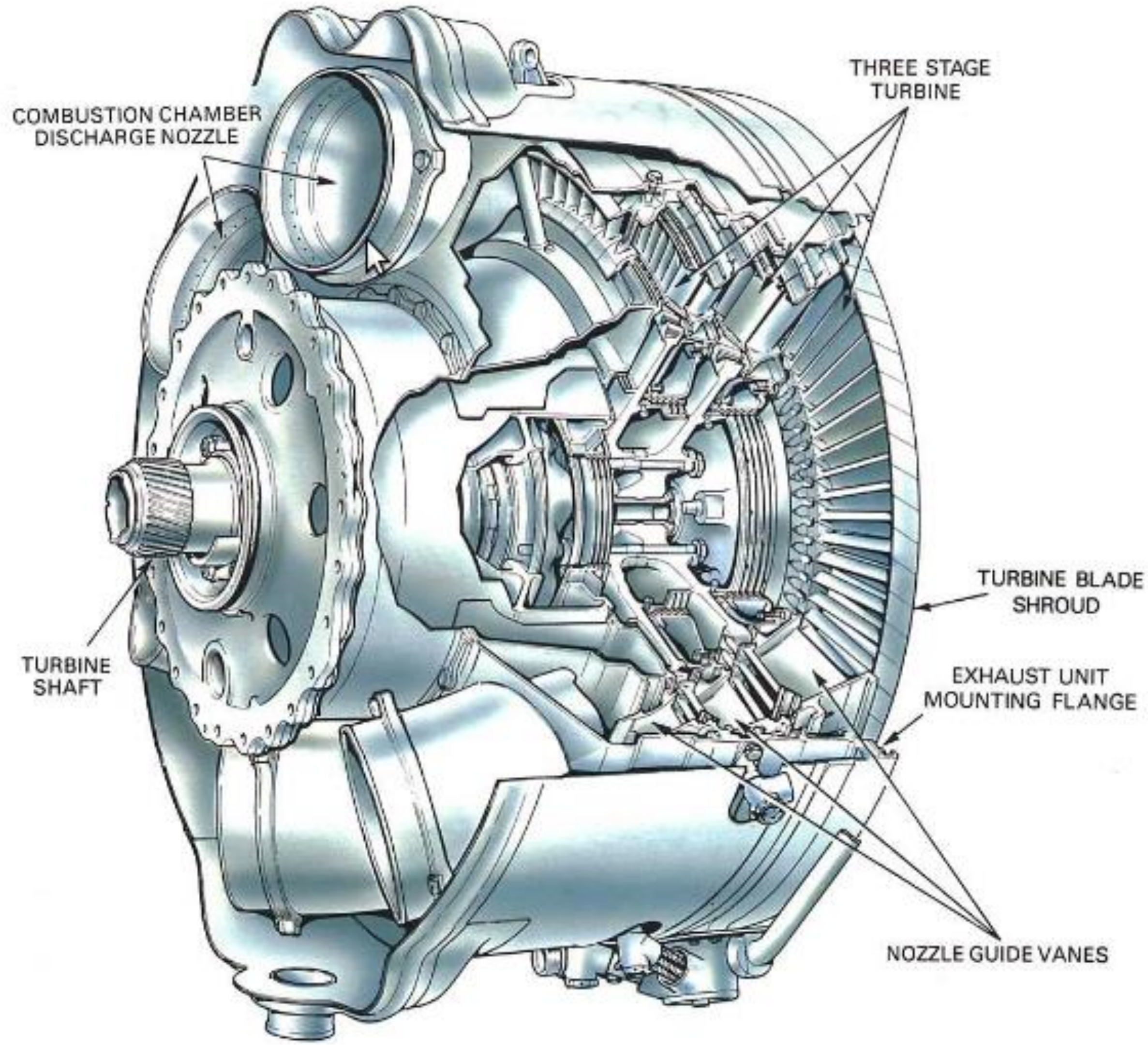
Axial flow turbines

- Turbines can be either axial, radial or mixed.
- Axial turbines can handle large mass flow rates and are more efficient.
- Axial turbine have same frontal area as that of the compressor.
- They can also be used with a centrifugal compressor.
- Efficiency of turbines higher than that of compressors.
- Turbines are in general aerodynamically “easier” to design.

Axial flow turbines

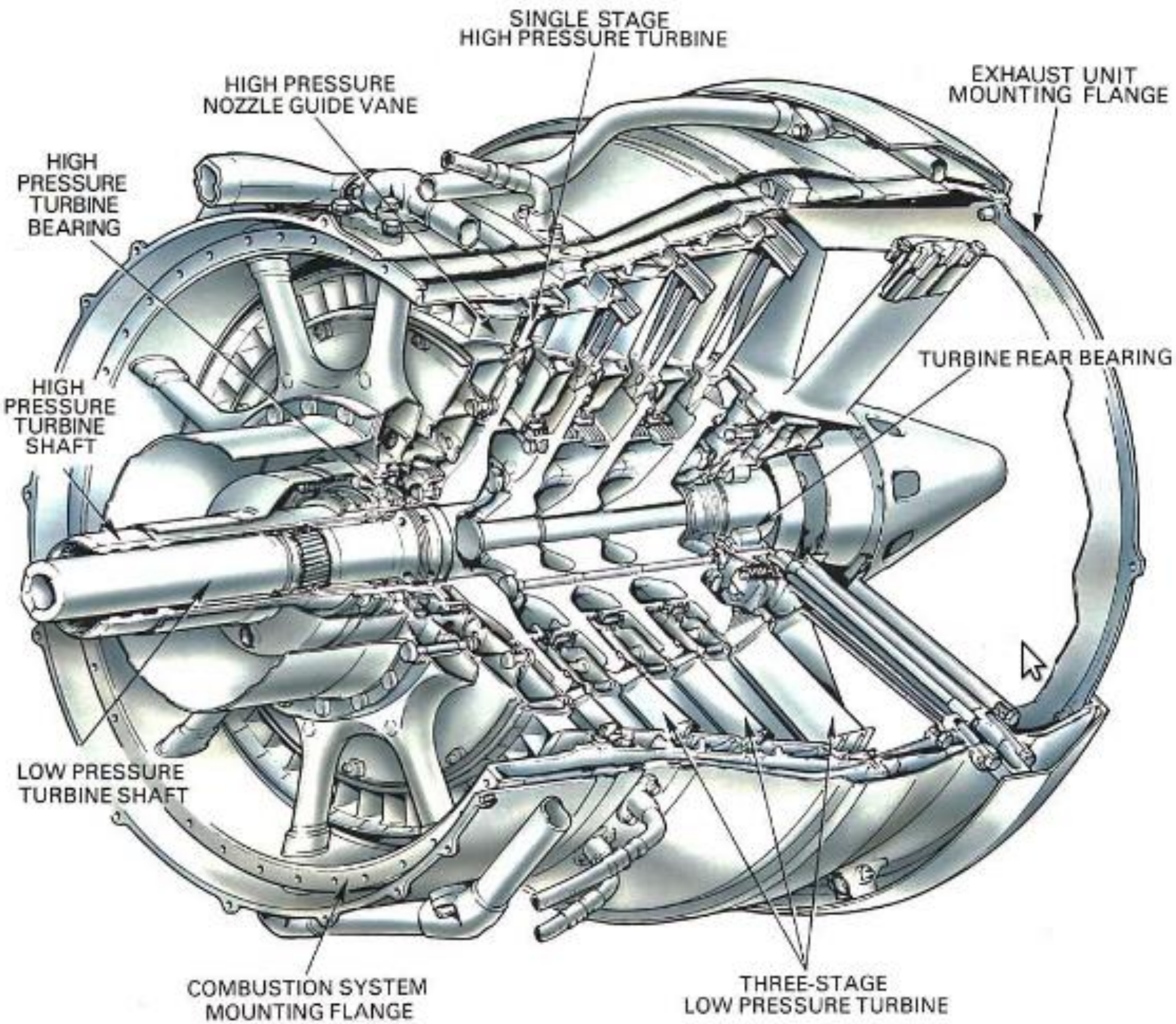


An axial turbine stage



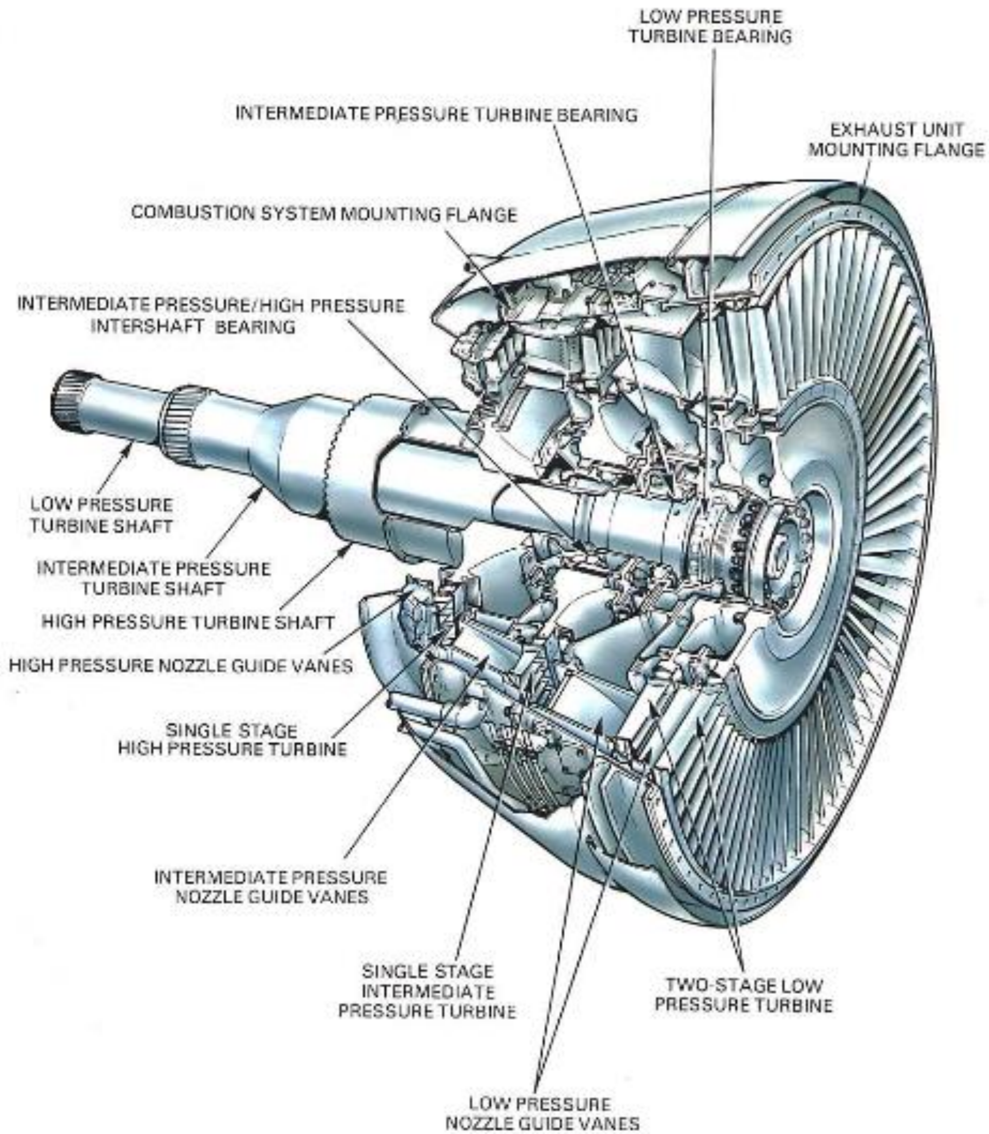
A 3 stage turbine with single shaft system

Source: The Jet Engine, Rolls Royce, 1996



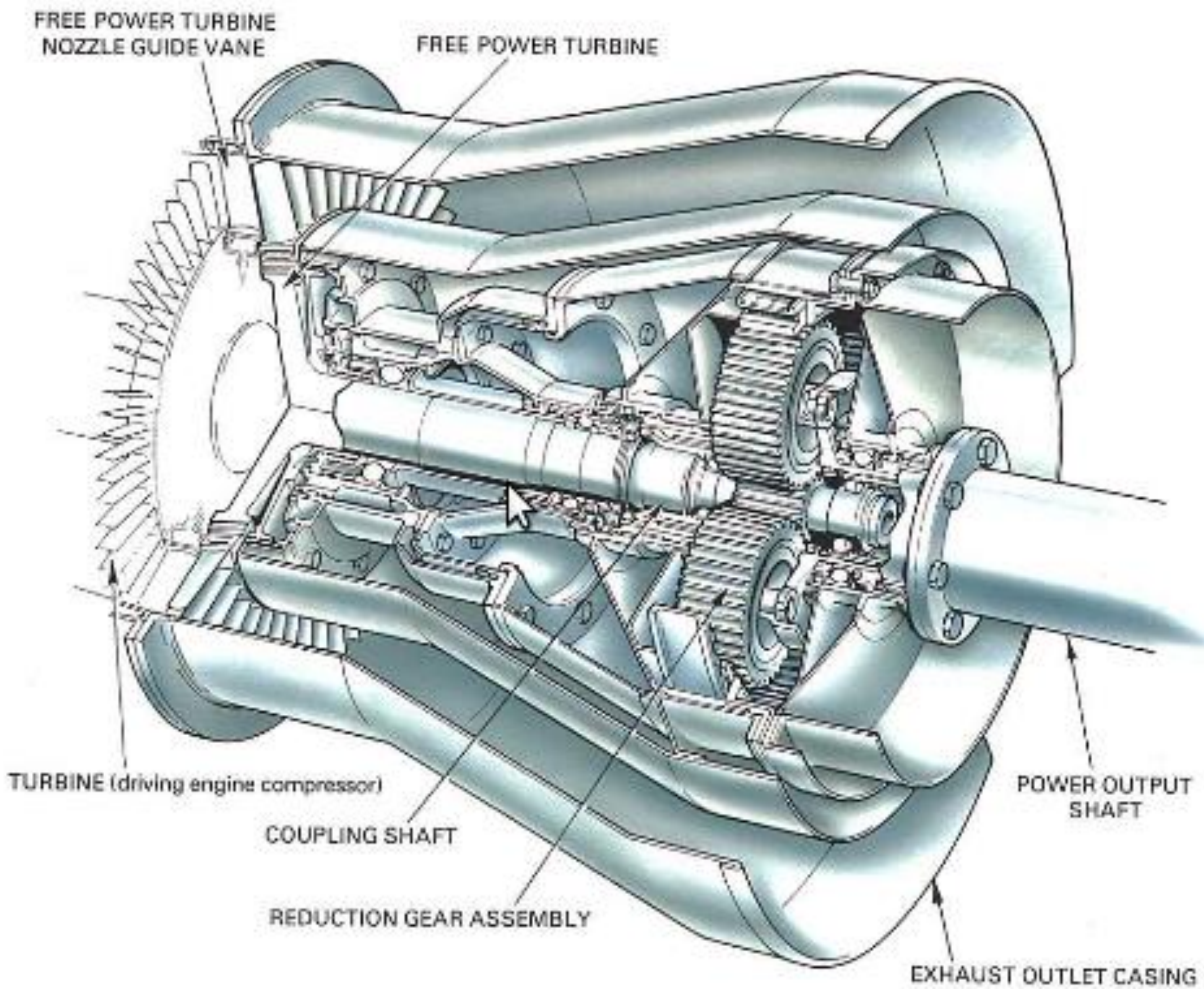
A twin turbine and shaft system

Source: The Jet Engine, Rolls Royce, 1996



A triple turbine and shaft system

Source: The Jet Engine, Rolls Royce, 1996



A free power turbine system

Source: The Jet Engine, Rolls Royce, 1996

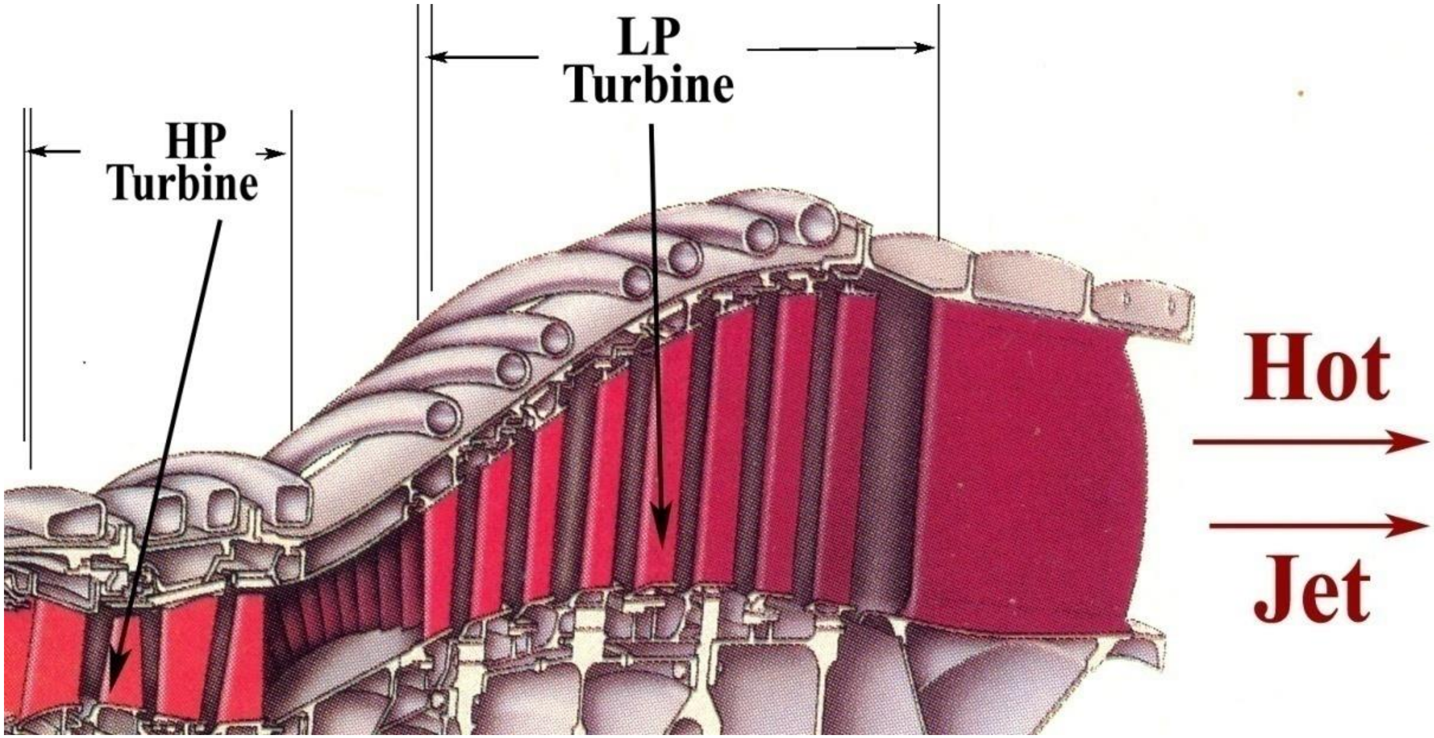
Shaft energy from the turbine is used to run:

i) A compressor, or a fan , which raises the internal energy content of the fluid before it goes into the combustor, for hot thrust

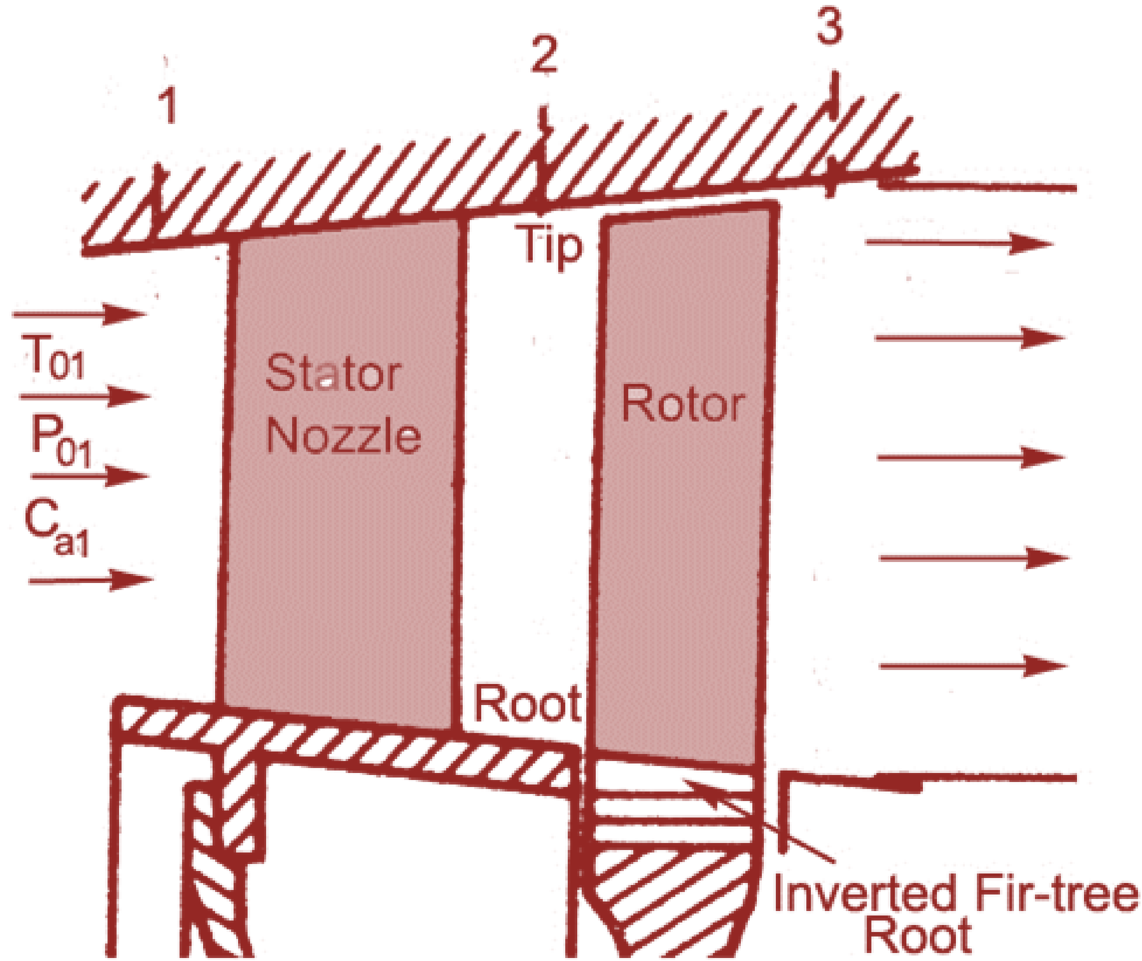
ii) A Fan that produces cold propulsive thrust

iii) A propeller to create the propulsive thrust

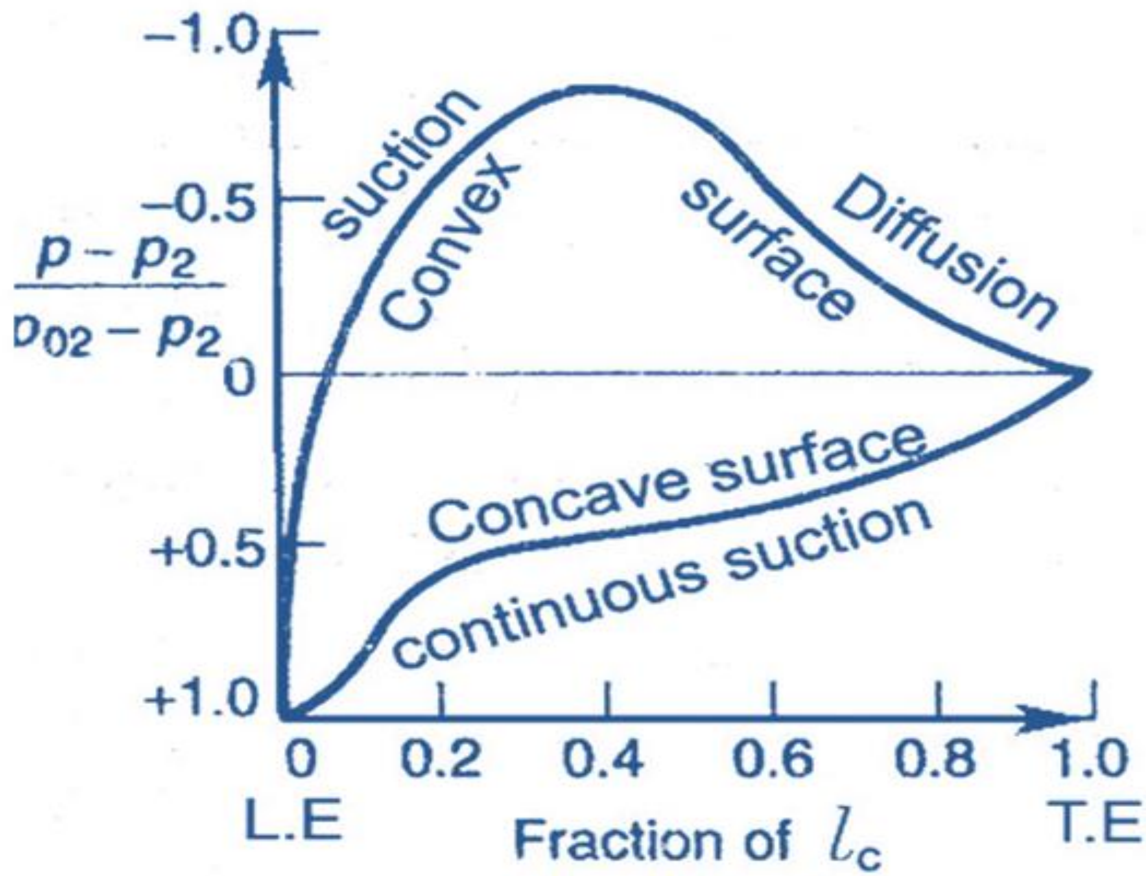
iv) A generator in a land based power generation unit



Multi-stage 2-spool axial turbine layout

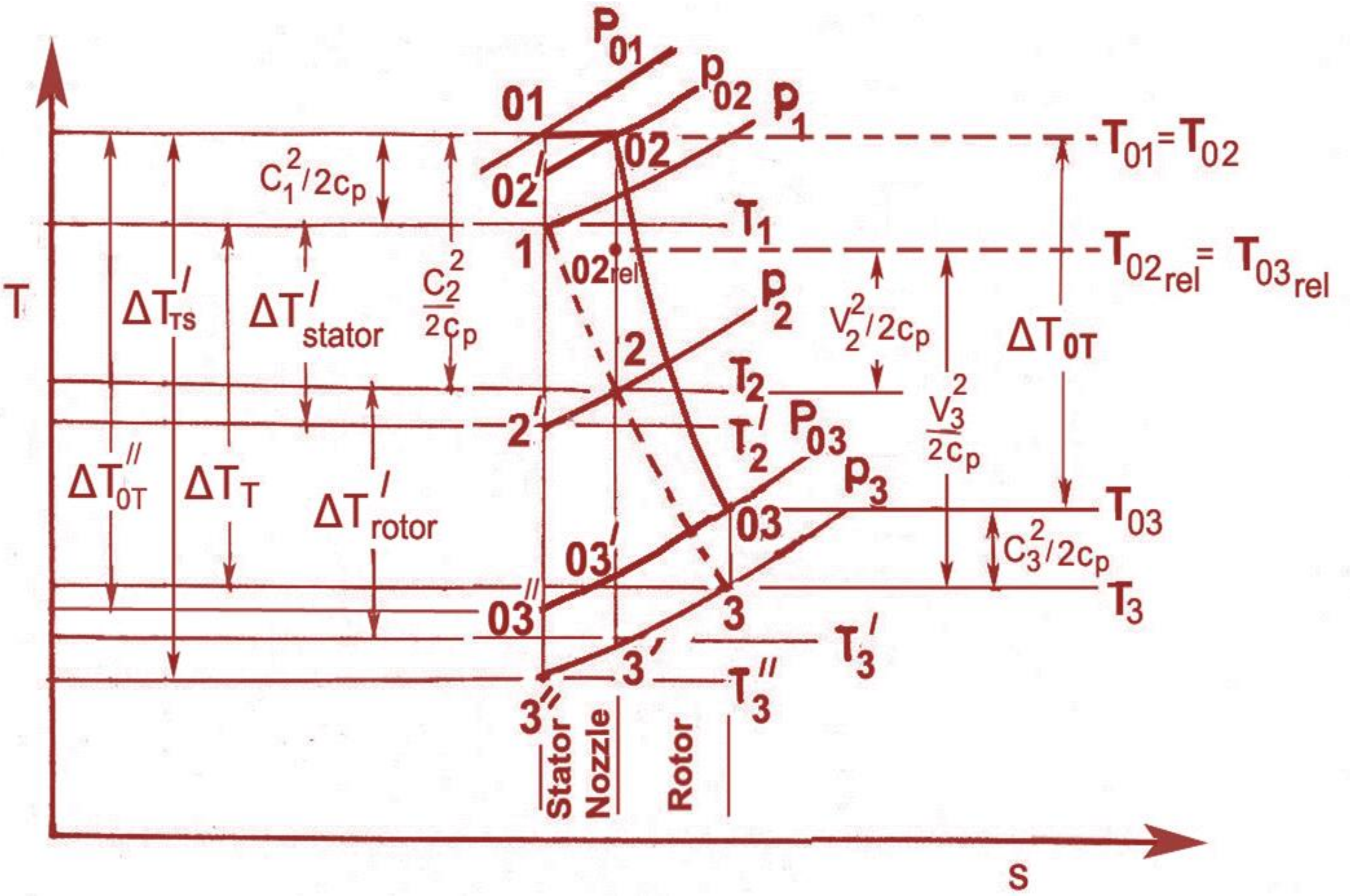


Elemental Turbine stage – Rotor + Stator



Flow over the blade surfaces

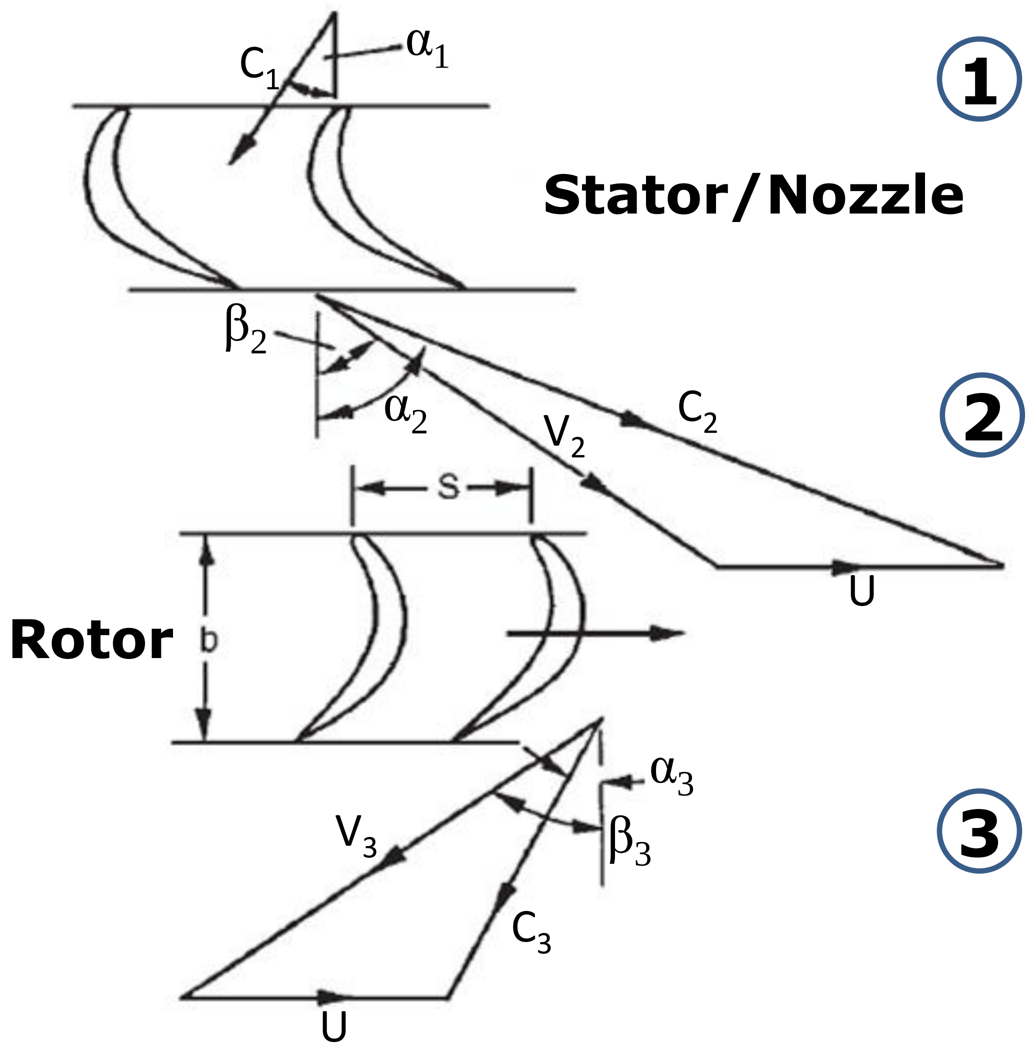
Thermodynamic changes in Turbine in a GTE Cycle



Velocity triangles

- Elementary analysis of axial turbines too begins with velocity triangles.
- The analysis will be carried out at the mean height of the blade, where the peripheral velocity or the blade speed is, *U.*
- The absolute component of velocity will be denoted by, *C* and the relative component by, *V.*
- The axial velocity (absolute) will be denoted by C_a and the tangential components will be denoted by subscript *w* (for eg, C_w or V_w)
- α denotes the angle between the absolute velocity with the axial direction and β the corresponding angle for the relative velocity.

Velocity triangles



Types of axial turbines

- There are two types of axial turbine configurations: Impulse and reaction
- Impulse turbine
  - Entire pressure drop takes place in the nozzle.
  - Rotor blades simply deflect the flow and hence have symmetrical shape.
- Reaction turbine
  - Pressure drop shared by the rotor and the stator
  - The amount of pressure drop shared is given by the degree of reaction.

Work and stage dynamics

Applying the angular momentum equation,

$$P = \dot{m}(U_2 C_{w2} - U_3 C_{w3})$$

In an axial turbine, $U_2 \approx U_3 = U$.

Therefore, the work per unit mass is

$$w_t = U(C_{w2} - C_{w3}) \quad \text{or} \quad w_t = c_p(T_{01} - T_{03})$$

Let $\Delta T_0 = T_{01} - T_{03} = T_{02} - T_{03}$

The stage work ratio is,

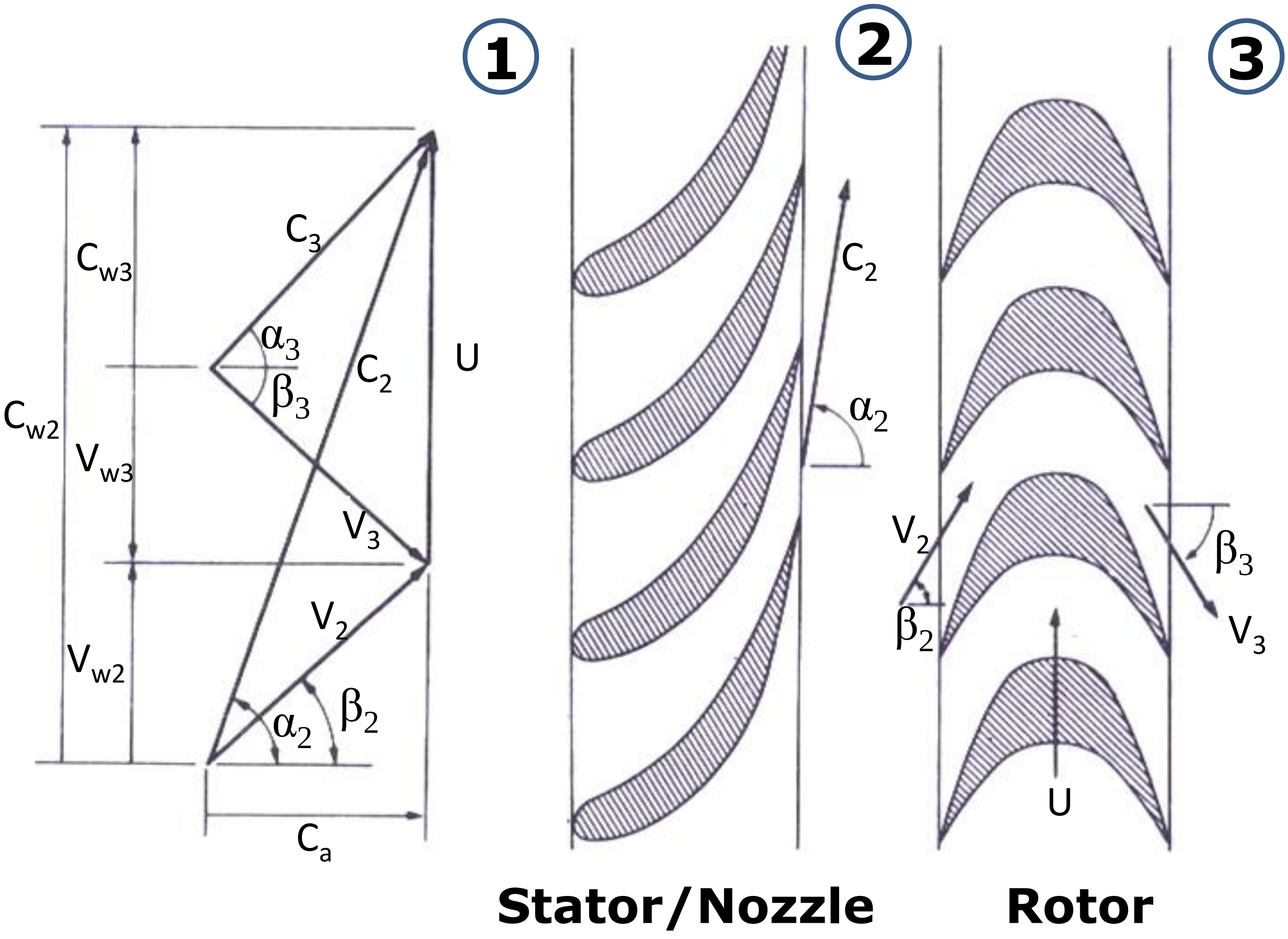
$$\frac{\Delta T_0}{T_{01}} = \frac{U(C_{w2} - C_{w3})}{c_p T_{01}}$$

Work and stage dynamics

- Turbine work per stage is limited by
  - Available pressure ratio
  - Allowable blade stresses and turning
- Unlike compressors, boundary layers are generally well behaved, except for local pockets of separation
- The turbine work ratio is also often defined in the following way:

$$\frac{w_t}{U^2} = \frac{\Delta h_0}{U^2} = \frac{C_{w2} - C_{w3}}{U}$$

Impulse turbine stage



Impulse turbine stage

In an impulse turbine, the rotor simply deflects the flow. Therefore,

$$\beta_3 = -\beta_2 \;\Rightarrow V_{w3} = -V_{w2}$$

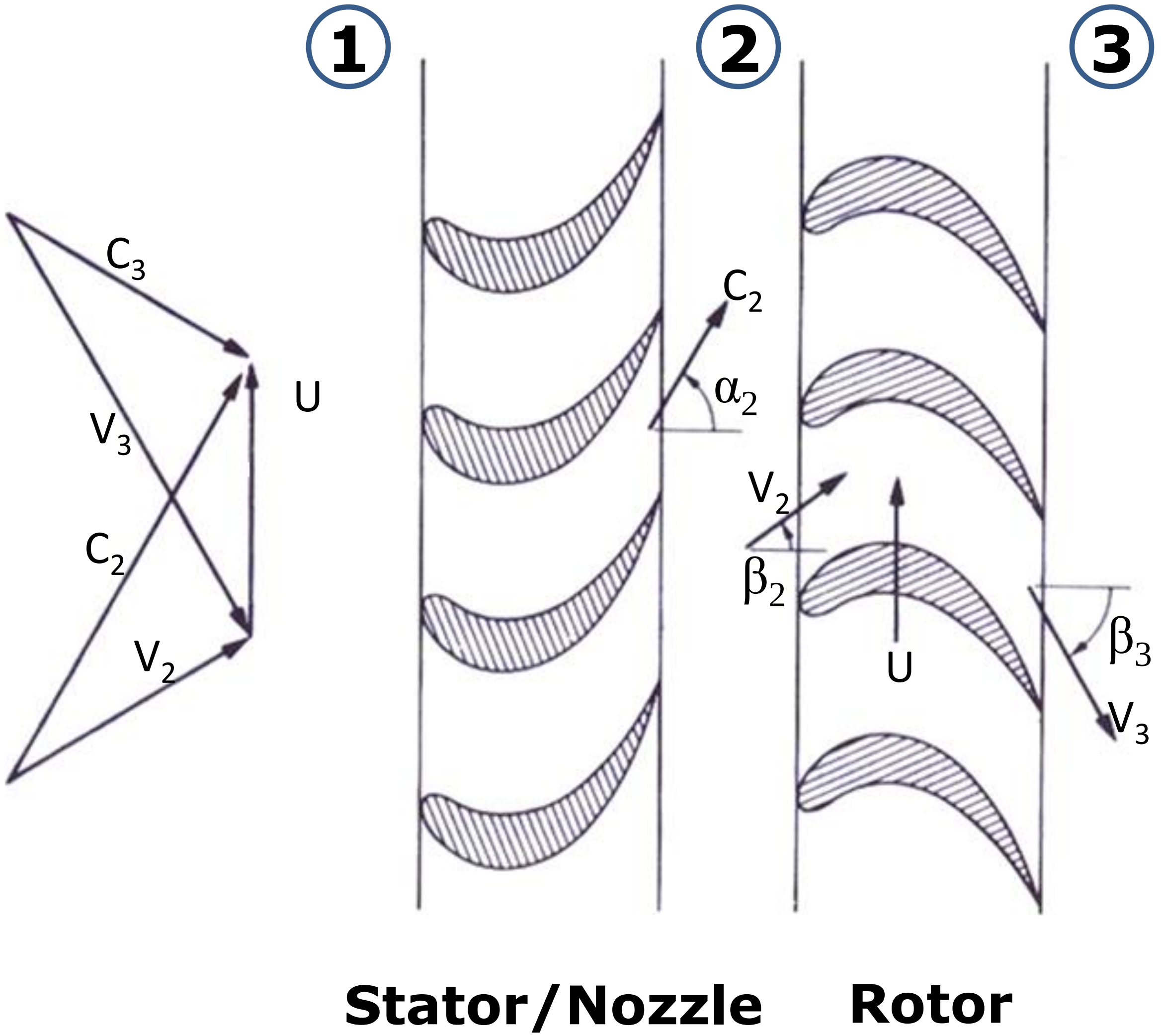
$$and \quad C_{w2} - C_{w3} = 2V_{w2} = 2(C_{w2} - U)$$

$$= 2U\left(\frac{C_a}{U}\tan\alpha_2 - 1\right)$$

Or, the turbine work ratio is

$$\frac{\Delta \mathrm{h}_0}{\mathrm{U}^2} = 2U\left(\frac{C_a}{U}\tan\alpha_2 - 1\right)$$

50% Reaction turbine stage



Impulse turbine stage

In a 50% reaction turbine, the velocity triangles are symmetrical. Therefore, for constant axial velocity,

$$C_{w3} = -(C_a \tan\alpha_2 - U)$$

And the turbine work ratio becomes

$$\frac{\Delta h_0}{U^2} = \left(2\frac{C_a}{U}\tan\alpha_2 - 1\right)$$