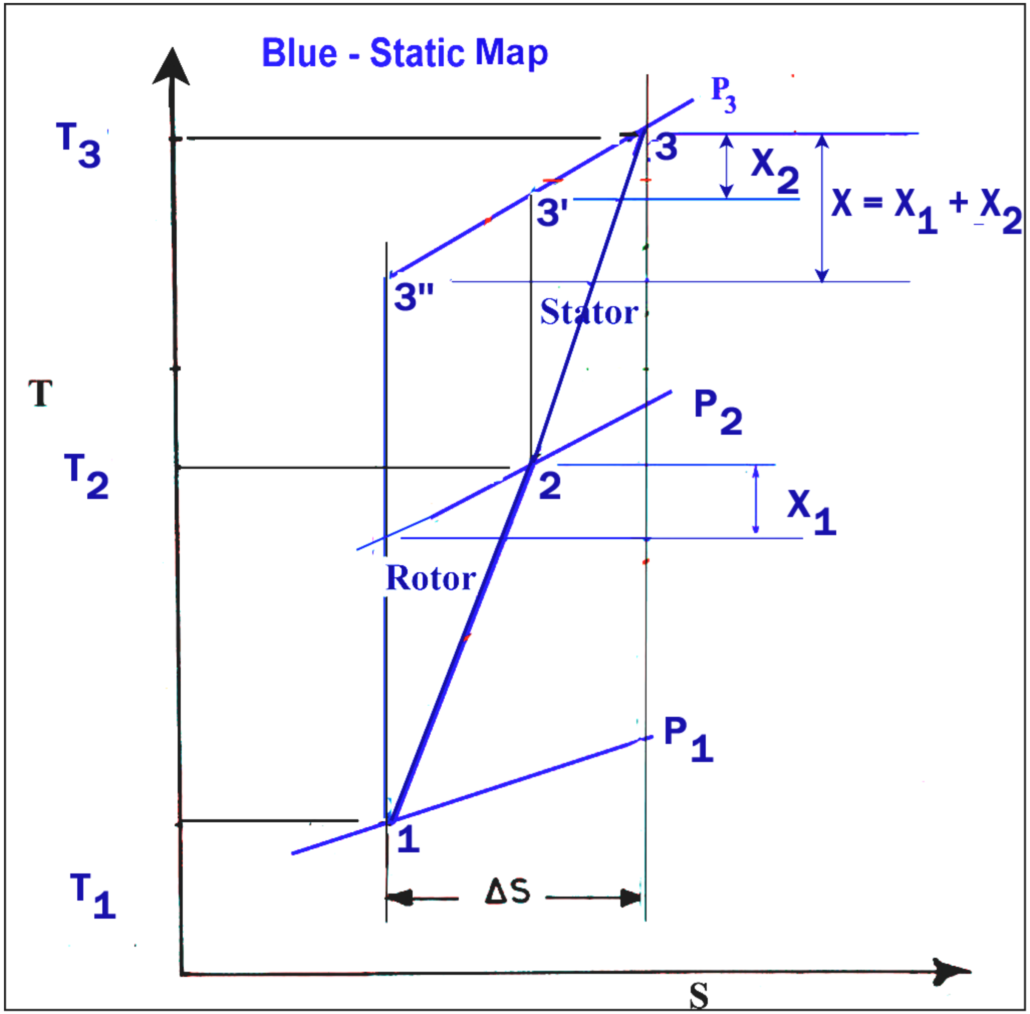
- Recap: Lecture 3: 28th July 2015, 1530-1655 hrs.
  - Energy equation, stagnation properties
  - Isentropic efficiency of compressor/fan
  - Isentropic efficiency of turbine
  - Polytropic efficiency of compressors and turbines
  - Thermodynamics of compression

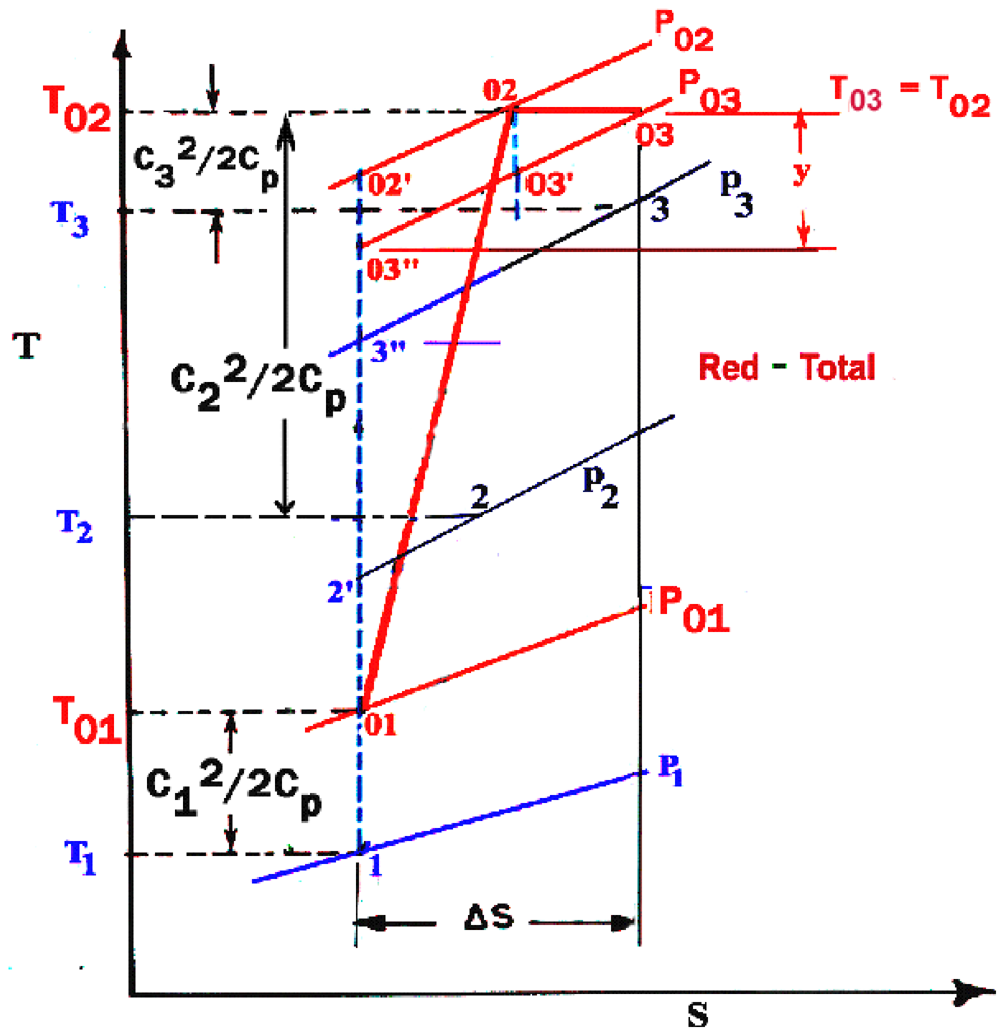
# Thermodynamics of compressors



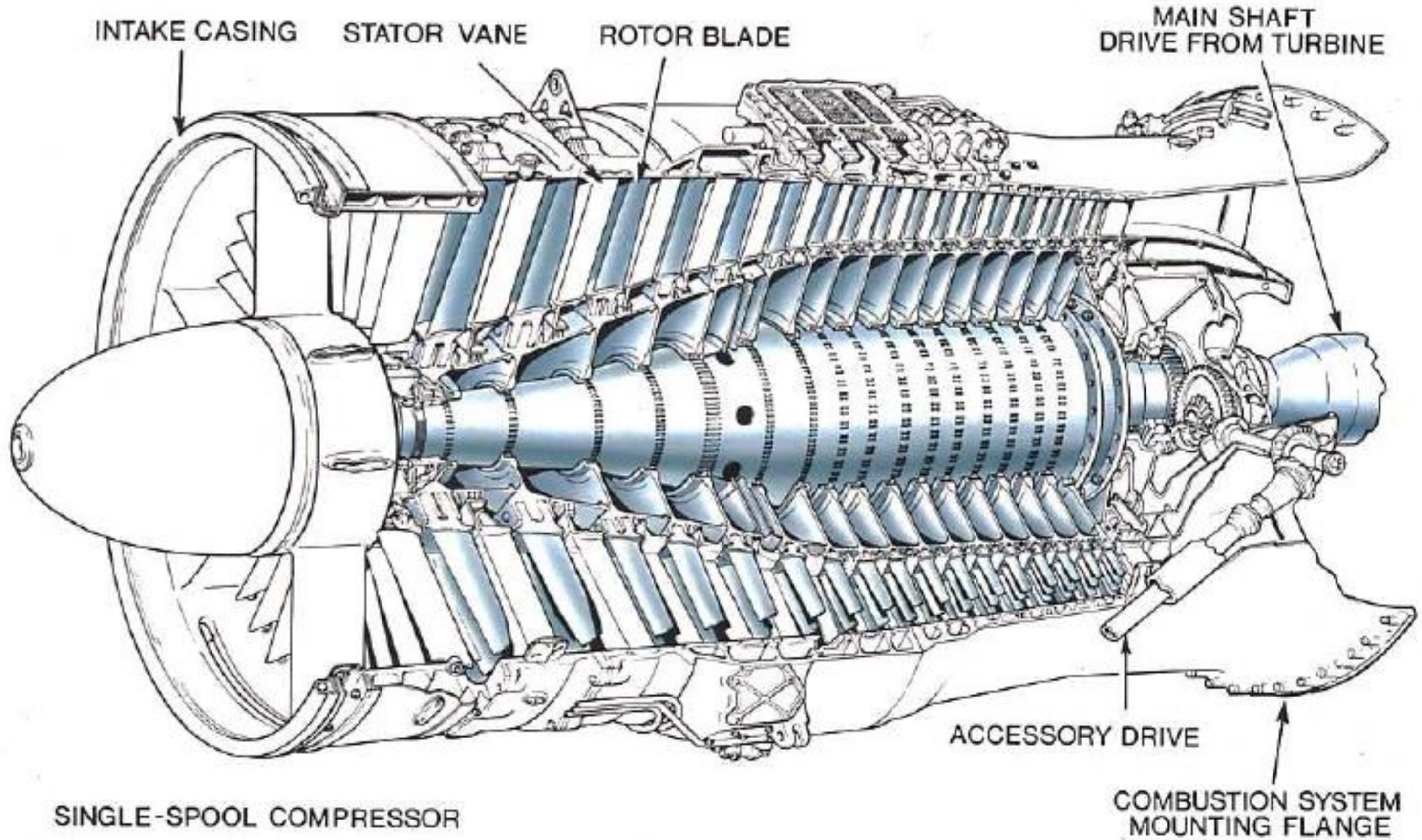

$X_1$ , $X_2$ are the losses in the rotor and the stator respectively

**Compression in terms of static parameters**

# Thermodynamics of compressors




**Compression in terms of total parameters**




**Typical multi-stage axial flow compressor**

Courtesy: *The Jet Engine*, Roll Royce Plc, 1996

# Basic operation of axial compressors

- The compression process consists of a series of diffusions.
- This occurs both in the rotor as well as the stator.
- Due to motion of the rotor blades→ two distinct velocity components: absolute and relative velocities in the rotor.
- The absolute velocity of the fluid is increased in the rotor, whereas the relative velocity is decreased, leading to diffusion.
- Per stage pressure ratio is limited because a compressor operates in an adverse pressure gradient environment.

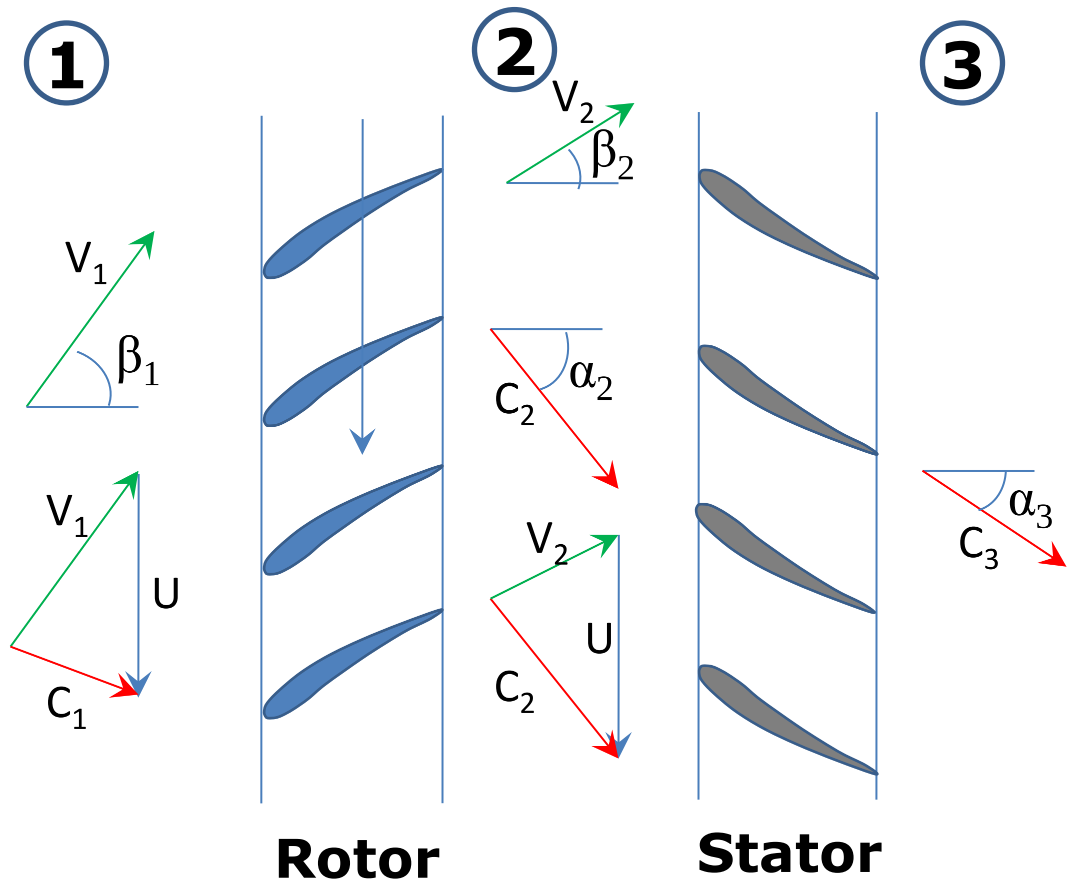
# Basic operation of axial compressors

- Turbines on the other hand operate under favourable pressure gradients.
- Several stages of an axial compressor can be driven by a single turbine stage.
- Careful design of the compressor blading is essential to minimize losses as well as to ensure stable operation.
- Some compressors also have inlet Guide Vanes (IGV) that permit the flow entering the first stage to vary under off-design conditions.

# Velocity triangles

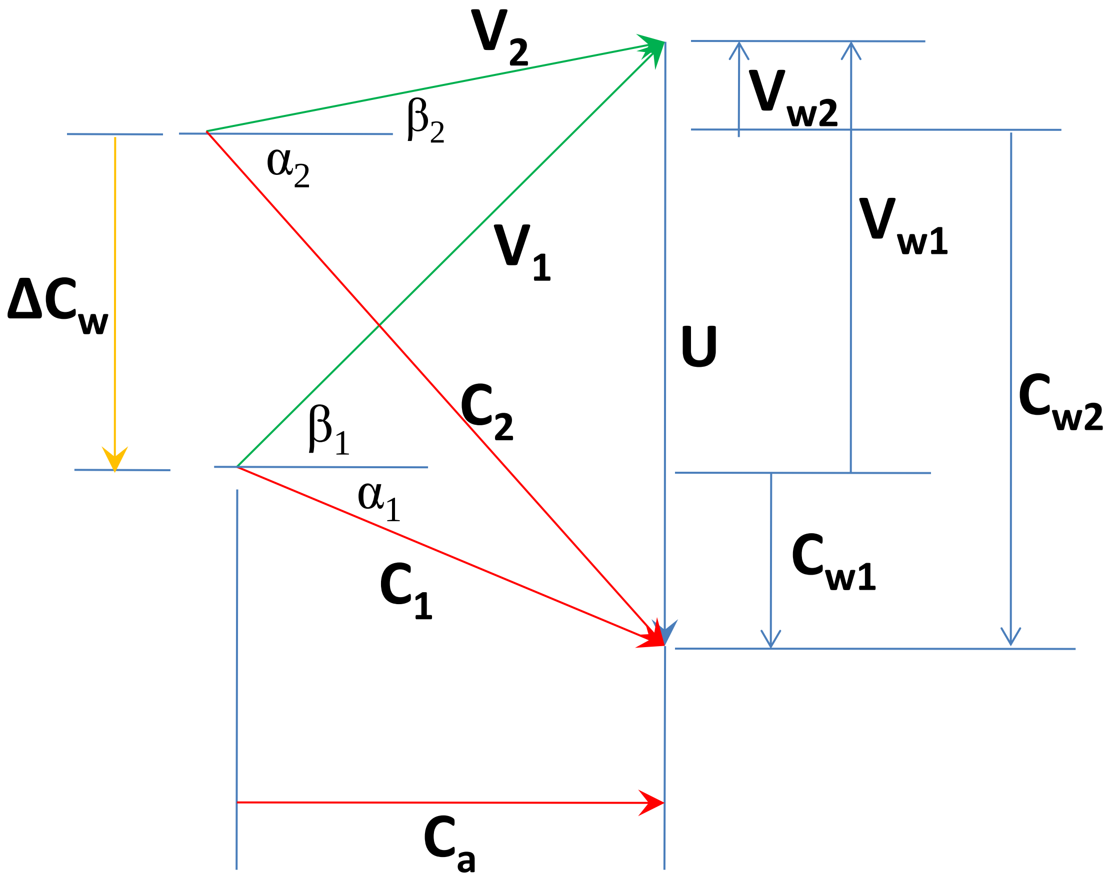
- Elementary analysis of axial compressors begins with velocity triangles.
- The analysis will be carried out at the mean height of the blade, where the peripheral velocity or the blade speed is, *U.*
- The absolute component of velocity will be denoted by, *C* and the relative component by, *V.*
- The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

# Velocity triangles

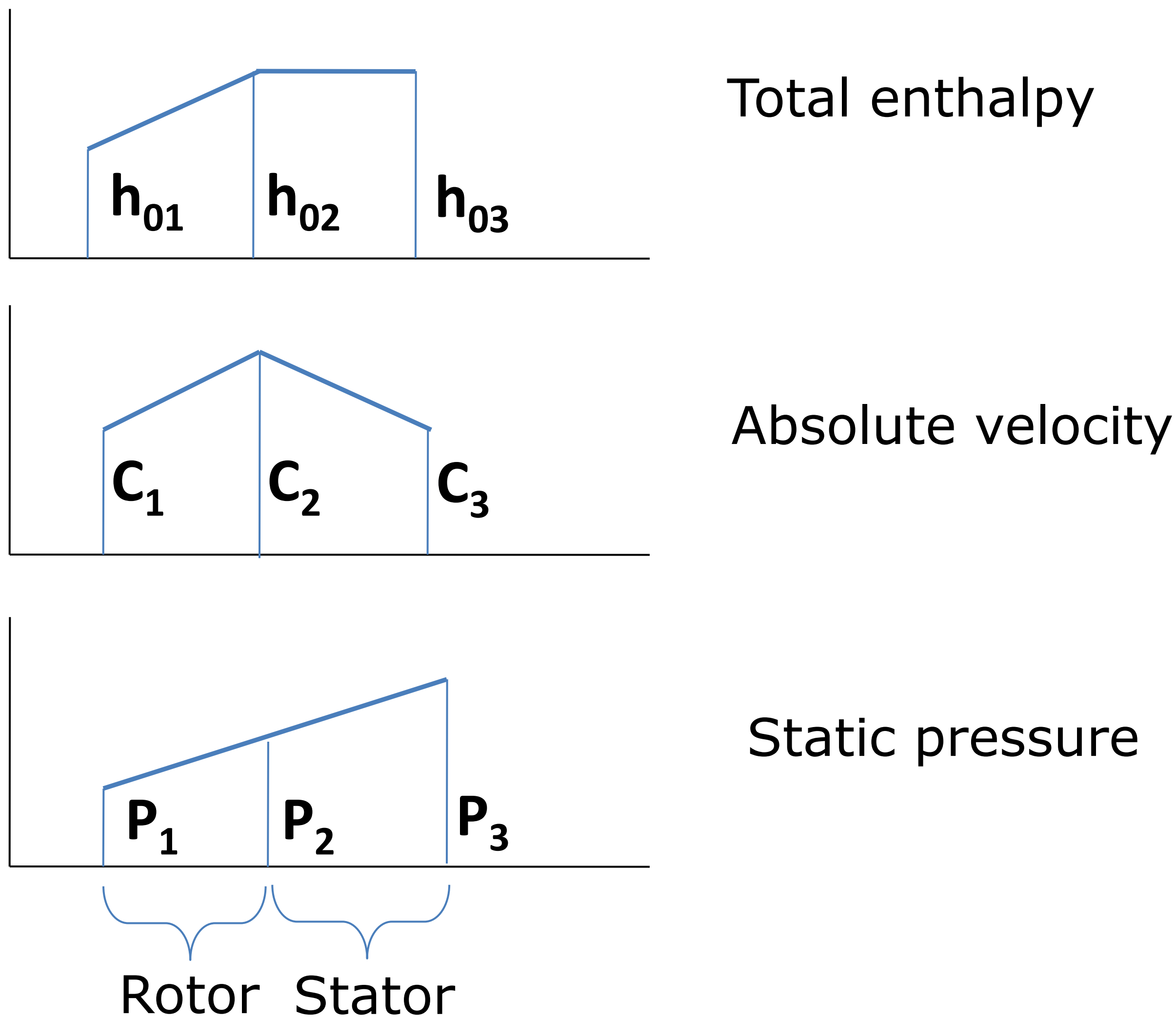



$$\vec{C} = \vec{U} + \vec{V}$$

# Velocity triangles



# Property changes across a stage



# Work and compression

- Assuming $C_a = C_{a1} = C_{a2}$, from the velocity triangles, we can see that

$$\frac{U}{C_a} = \tan\alpha_1 + \tan\beta_1 \quad \text{and} \quad \frac{U}{C_a} = \tan\alpha_2 + \tan\beta_2$$

- By considering the change in angular momentum of the air passing through the rotor, work done per unit mass flow is

$w = U(C_{w2} - C_{w1})$, where $C_{w1}$ and $C_{w2}$ are the tangential components of the fluid velocity before and after the rotor, respectively.

# Work and compression

The above equation can also be written as,

$$w = UC_a(\tan\alpha_2 - \tan\alpha_1)$$

Since, $(\tan\alpha_2 - \tan\alpha_1) = (\tan\beta_1 - \tan\beta_2)$

$$\therefore w = UC_a(\tan\beta_1 - \tan\beta_2)$$

In other words, $w = U\Delta C_w$

- The input energy will reveal itself in the form of rise in stagnation temperature of the air.
- The work done as given above will also be equal to the change in stagnation enthalpy across the stage.

# Work and compression

$$h_{02} - h_{01} = U\Delta C_w$$

$$T_{02} - T_{01} = \frac{U\Delta C_w}{c_p} \Rightarrow \frac{\Delta T_0}{T_{01}} = \frac{U\Delta C_w}{c_p T_{01}}$$

Since the flow is adiabatic and no work is done as the fluid passes through the stator, $T_{03} = T_{02}$

Let us define stage efficiency, $\eta_{st}$, as

$$\eta_{st} = \frac{h_{03s} - h_{01}}{h_{03} - h_{01}}$$

This can be expressed as

$$\frac{T_{03s}}{T_{01}} = 1 + \eta_{st} \frac{\Delta T_0}{T_{01}}$$

# Work and compression

In the above equation, $\Delta T_0 = T_{03} - T_{01}$

In terms of pressure ratio,

$$\frac{P_{03}}{P_{01}} = \left[1 + \eta_{st} \frac{\Delta T_0}{T_{01}}\right]^{\gamma/(\gamma-1)}$$

This can be combined with the earlier equation to give,

$$\frac{P_{03}}{P_{01}} = \left[1 + \eta_{st} \frac{U \Delta C_w}{c_p T_{01}}\right]^{\gamma/(\gamma-1)}$$

# Work and compression

- From the above equation that relates the per stage temperature rise to the pressure ratio, it can be seen that to obtain a high temperature ratio for a given overall pressure ratio (for minimizing number of stages),
  - High blade speed: limited by blades stresses
  - High axial velocity, high fluid deflection $(\beta_1-\beta_2)$: Aerodynamic considerations and adverse pressure gradients limit the above.