TURBOMACHINERY AERODYNAMICS

Lect- 2

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In this lecture...

- Axial flow compressors and fans
  - Thermodynamics of compression
    - P-v and T-s diagrams of compressors
    - Thermodynamics of compression process
    - Multi-stage compression
  - Basic operation of axial compressors/fans
  - Velocity triangles
  - Work and compression

Introduction

- Simplified aero-thermodynamic analysis
  - Optimised cycle design to precede the detailed component design
  - Prediction of work requirements
  - Efficiency of the compressor
  - Enables faster design modifications

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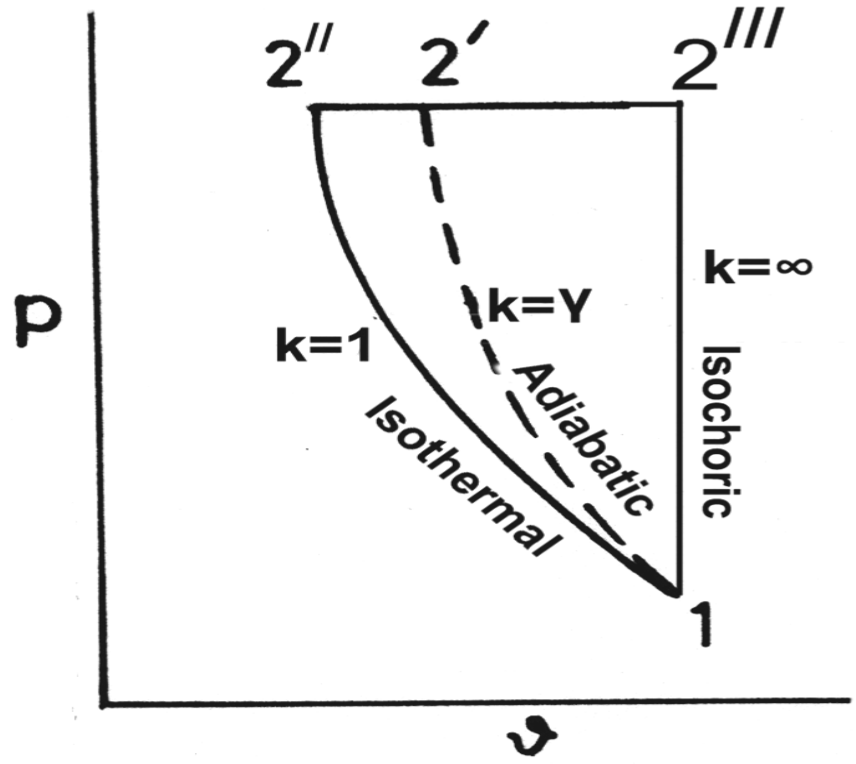
Thermodynamics of compression

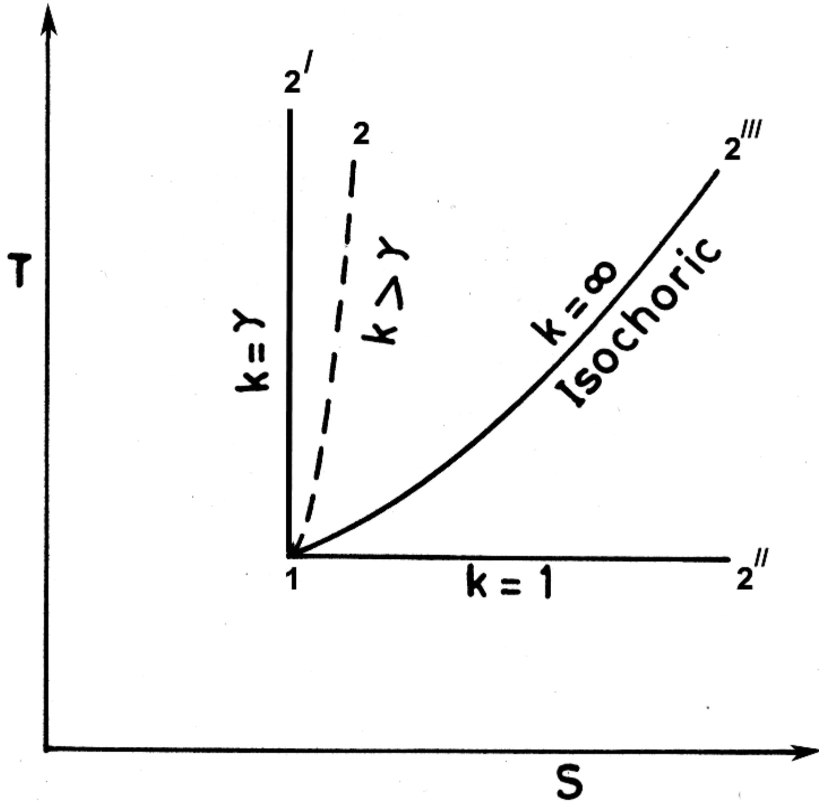


(i) Adiabatic (process 1-2$^{/}$) , $Pv^{\gamma}=c$

(ii) Isothermal process (1-2$^{//}$), $Pv=c$

(iii) Isochoric (Process 1-2$^{///}$), $Pv^{\infty}=c$

Thermodynamics of compressors



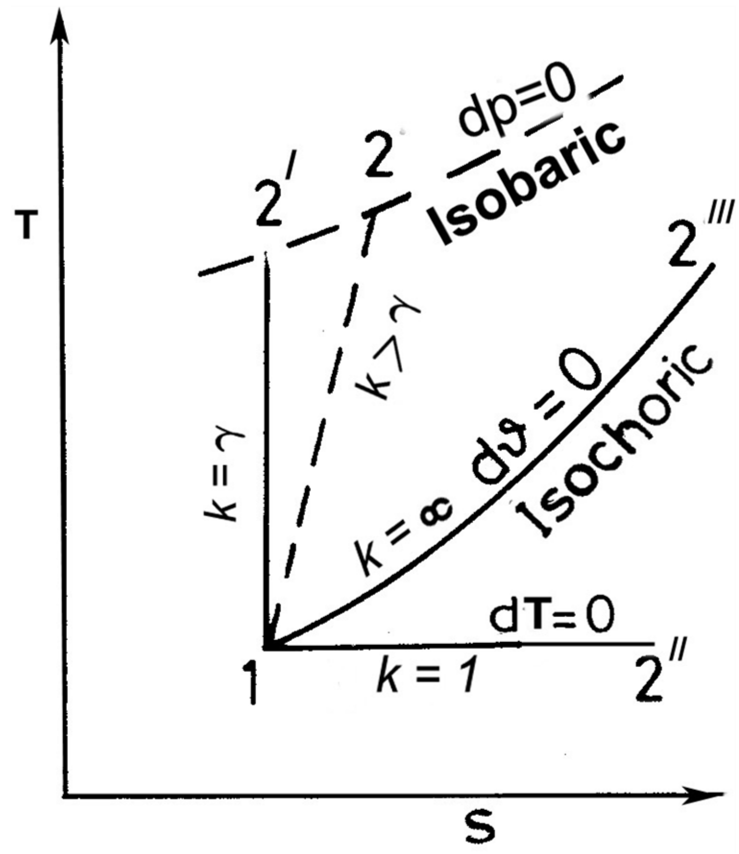
i) Isentropic process (1-2$^{/}$)

ii) Polytropic process (1-2)

iii) Isothermal process (1-2$^{//}$)

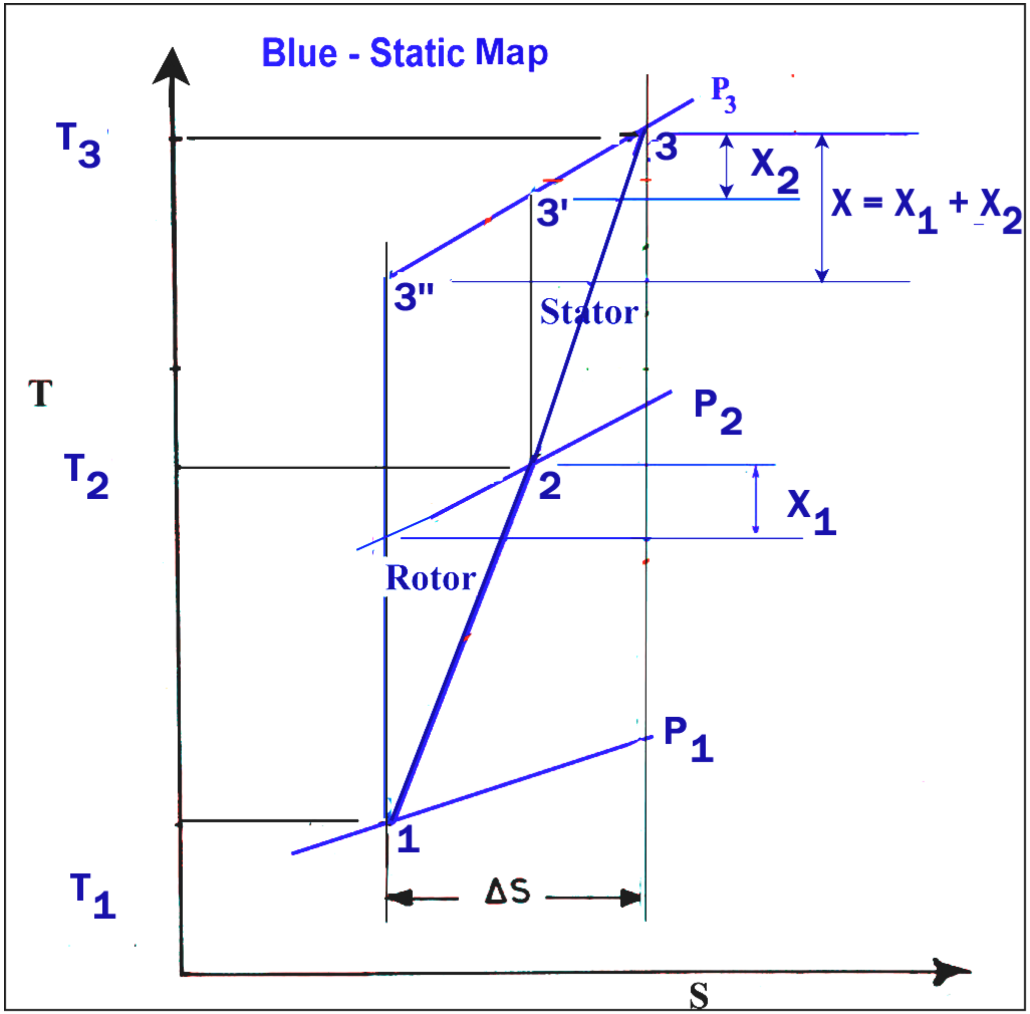
iv) Isochoric Process (1-2$^{///}$)

Thermodynamics of compressors



- The compression process is usually expressed in H-s or T-s diagrams.
- The ideal compression process is assumed to be isentropic.
- Deviation from this is expressed as isentropic efficiency.

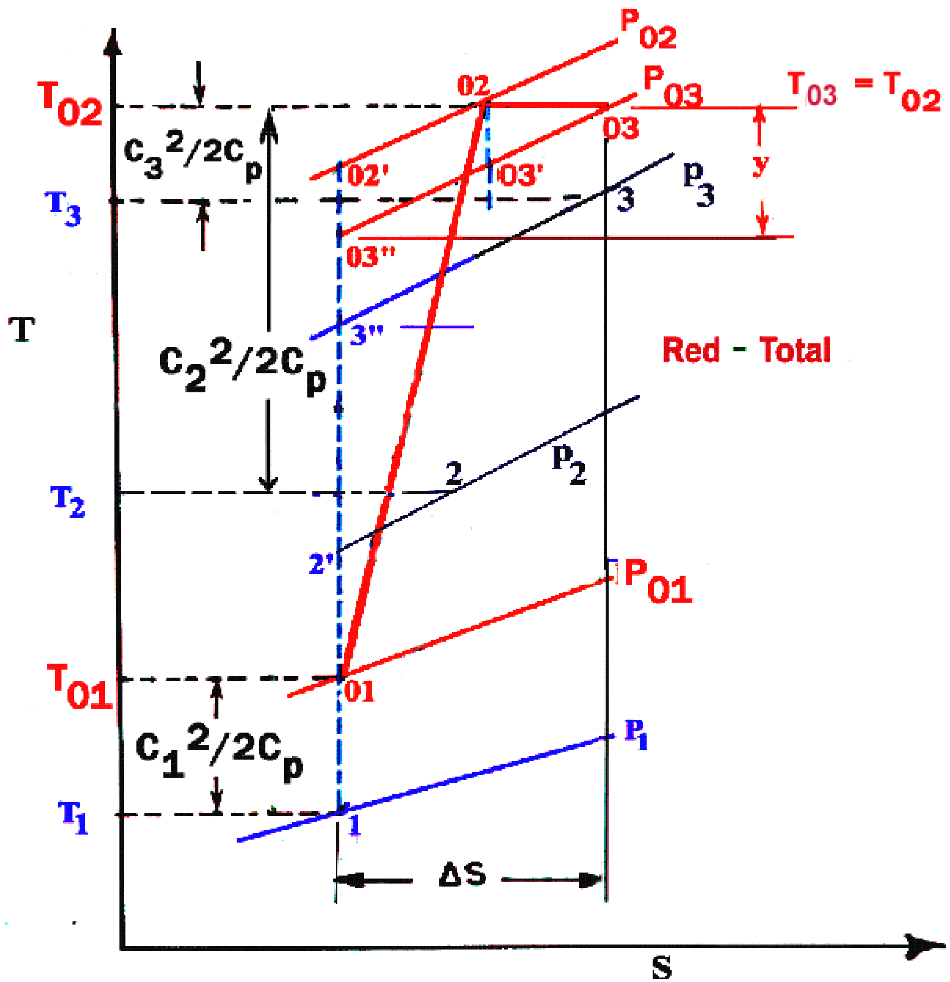
Thermodynamics of compressors



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

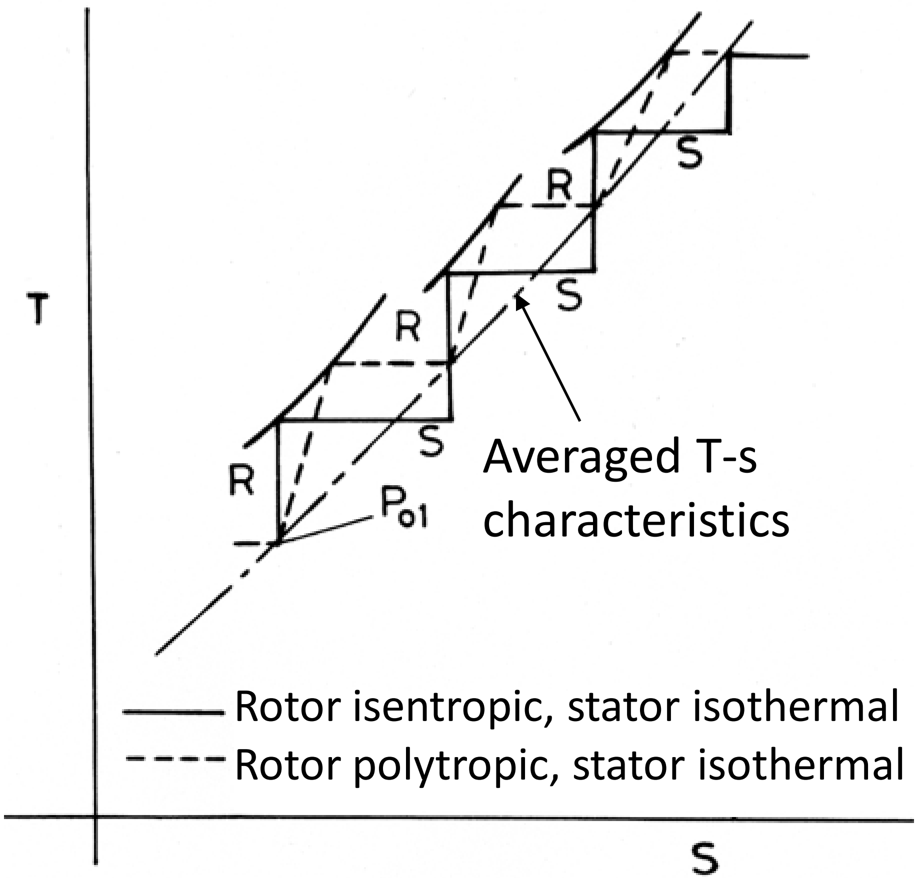
Compression in terms of static parameters

Thermodynamics of compressors



Compression in terms of total parameters

Thermodynamics of multi-stage compressors



- The flow at the rotor exit with high kinetic energy is still to be converted to static pressure through diffusion.
- The exit kinetic energy of a compressor is of the same order as the entry kinetic energy and the entire work input is expected to be converted to pressure.

Basic operation of axial compressors

- Axial flow compressors usually consists of a series of stages.
- Each stage comprises of a row of rotor blades followed by a row of stator blades.
- The working fluid is initially accelerated by the rotor blades and then decelerated in the stator passages.
- In the stator, the kinetic energy transferred in the rotor is converted to static pressure.
- This process is repeated in several stages to yield the necessary overall pressure ratio.

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)
- α denotes the angle between the absolute velocity with the axial direction and β the corresponding angle for the relative velocity.

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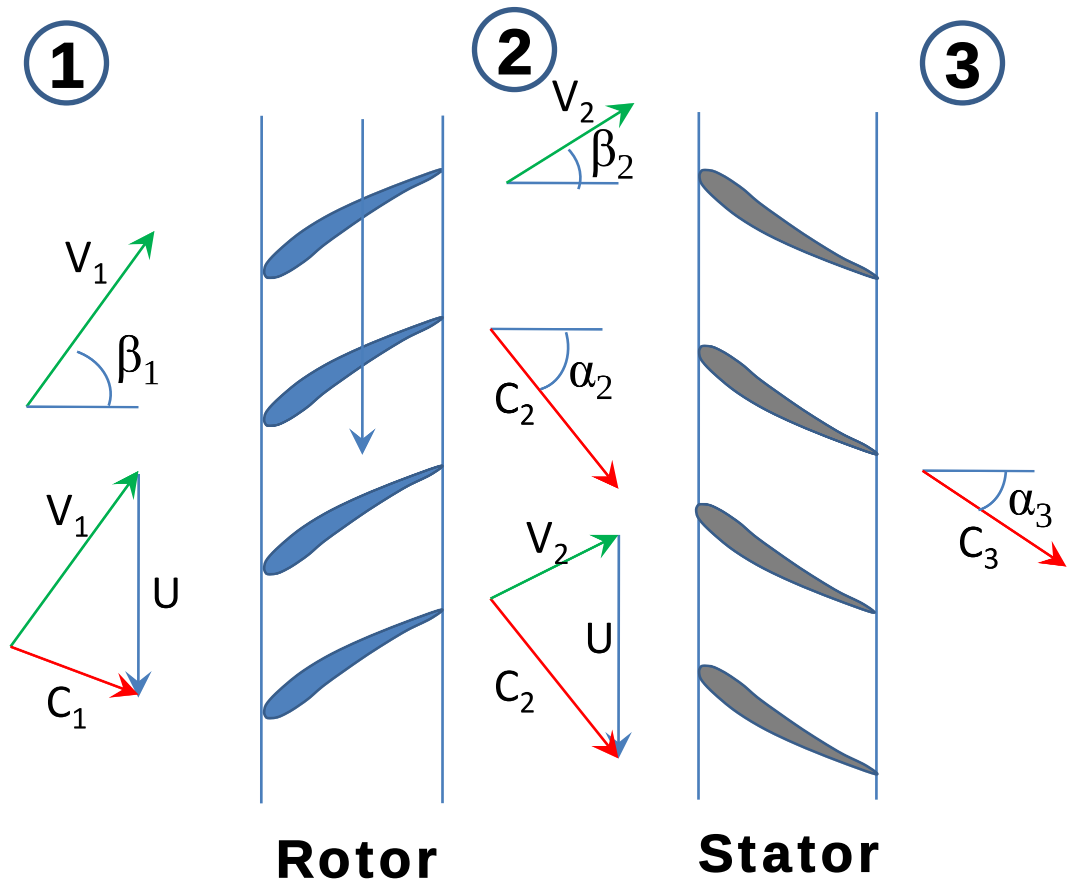
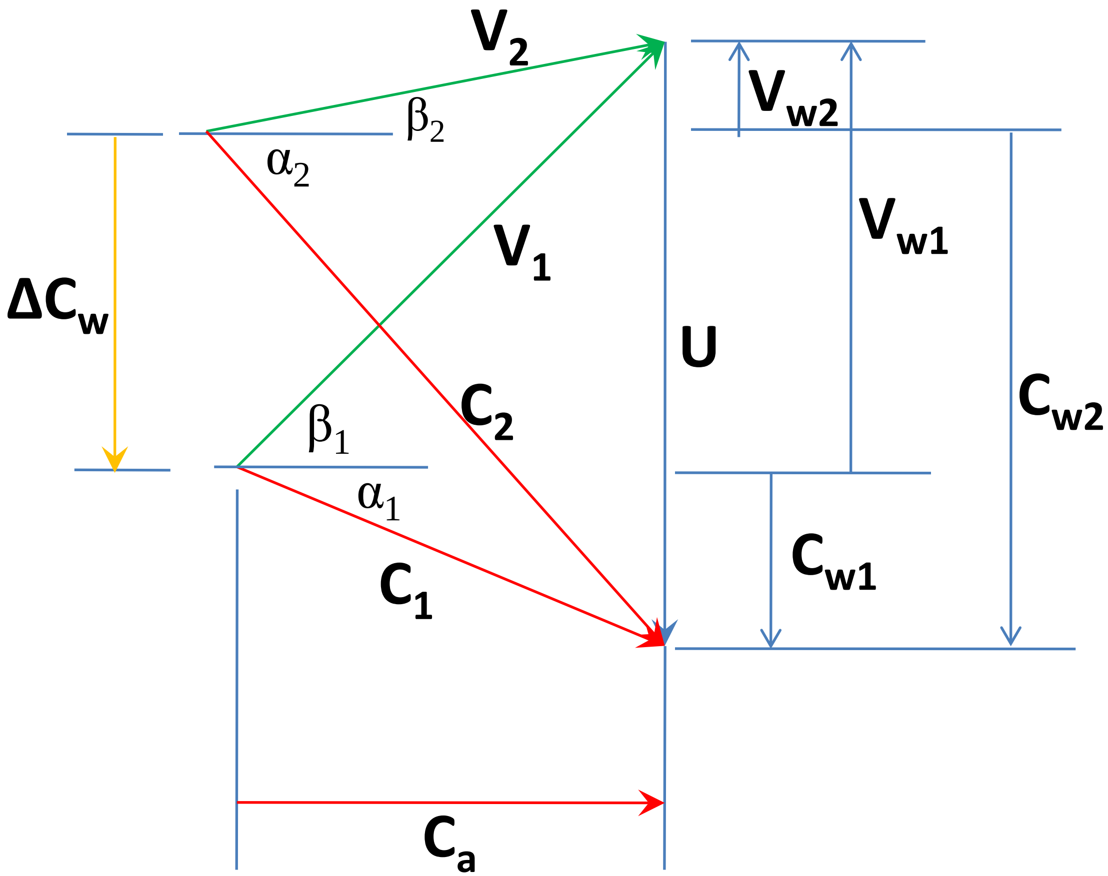
Velocity triangles

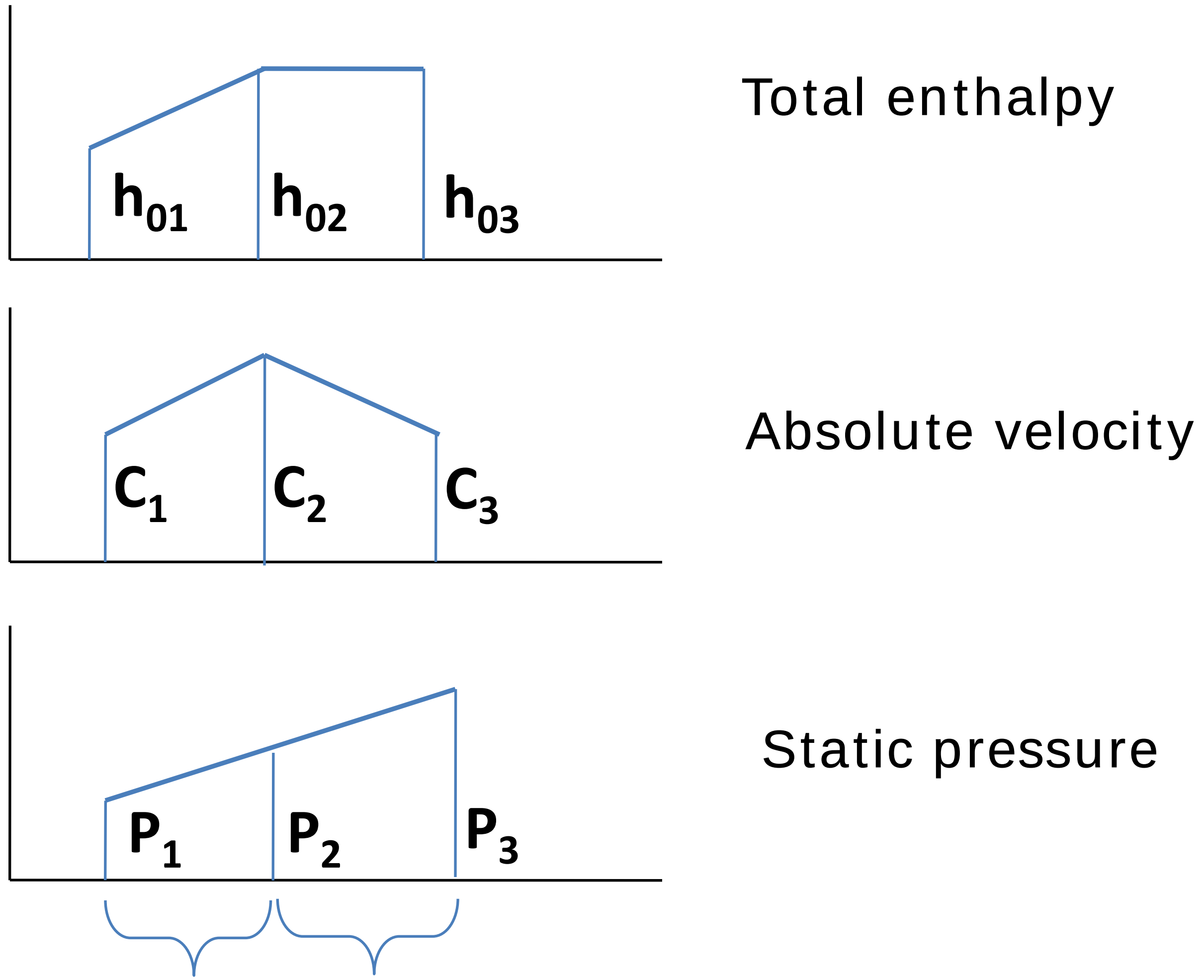


$$\vec{C} = \vec{U} + \vec{V}$$

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.

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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, η_{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 *(β_1-β_2):* Aerodynamic considerations and adverse pressure gradients limit the above.

Work and compression

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In the next lecture...

- Two-dimensional analytical model
- Performance parameters
- Cascade aerodynamics