Jet Aircraft Propulsion

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Lect-18

In this lecture...

- Elements of centrifugal compressors

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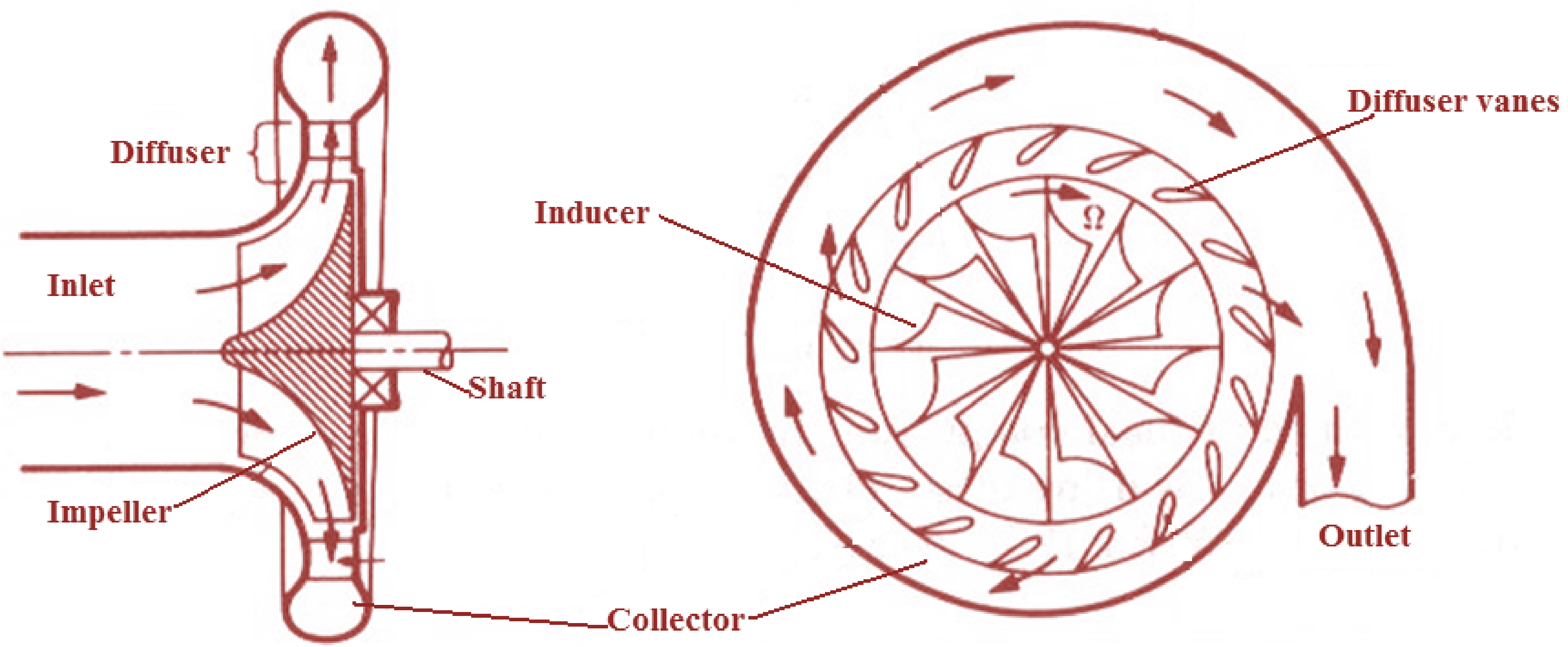
Centrifugal compressors

- Centrifugal compressors were used in the first jet engines developed independently by Frank Whittle and Hans Ohain.
- Centrifugal compressors still find use in smaller gas turbine engines.
- For larger engines, axial compressors need lesser frontal area and are more efficient.
- Centrifugal compressors can develop higher per stage pressure ratios.

Centrifugal compressors stage



Schematic of a typical centrifugal compressor

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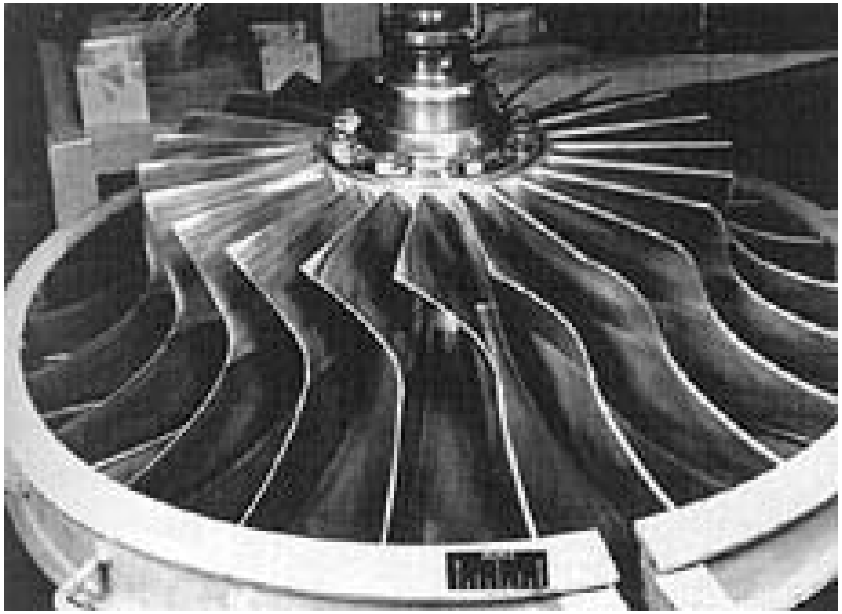
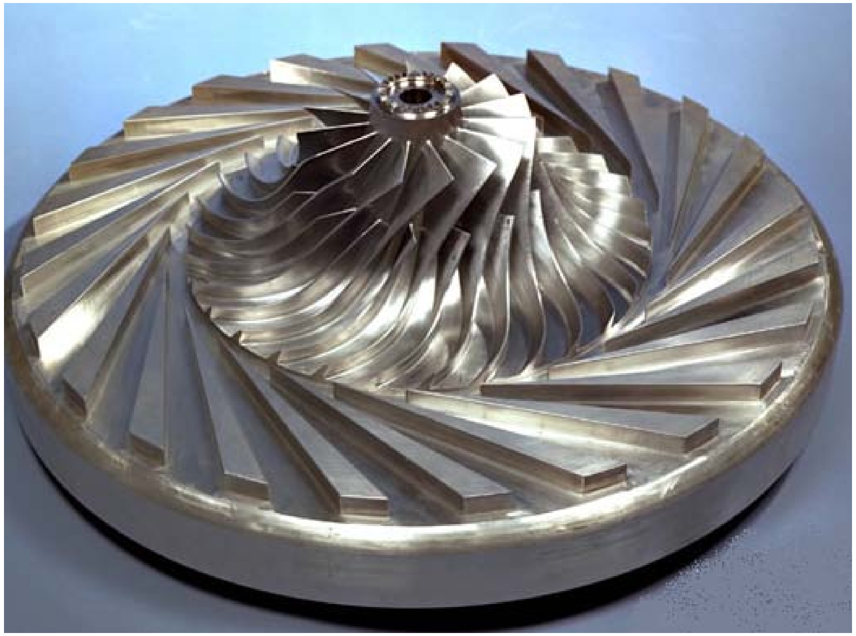
Centrifugal compressors stage





Typical centrifugal compressor rotors

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Centrifugal compressor stage

The torque applied on the fluid by the rotor

$\tau = \dot{m}\left[(rC_w)_2 - (rC_w)_1\right]$, where 1 and 2 denotes the compressor inlet and outlet, respectively.

The total work per unit mass is therefore,

$$w = \Omega\tau/\dot{m} = \Omega\left[(rC_w)_2 - (rC_w)_1\right]$$

$or,\ w = (UC_w)_2 - (UC_w)_1$ in which, $U = \Omega r$

From the steady flow energy equation,

$$w = h_{02} - h_{01} = h_2 - h_1 + \frac{C_2^2}{2} - \frac{C_1^2}{2}$$

$$or,\ h_2 - h_1 = (UC_w)_2 - (UC_w)_1 - \frac{C_2^2}{2} + \frac{C_1^2}{2}$$

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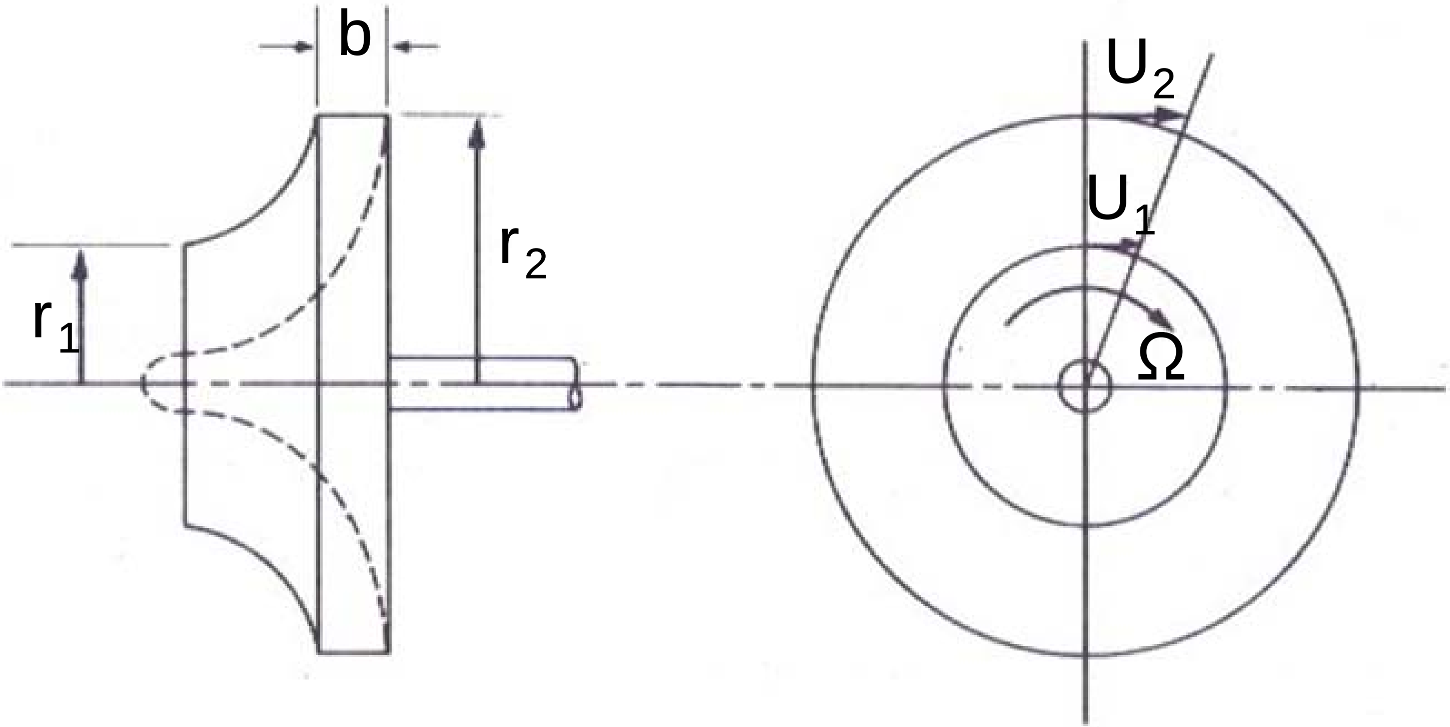
Centrifugal compressor stage



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Centrifugal compressor stage

The above equation gets transformed to,

$$h_2 - h_1 = \frac{U_2^2}{2} - \frac{U_1^2}{2} - \left(\frac{V_2^2}{2} - \frac{V_1^2}{2} \right)$$

$$i.e., \quad dh = d\left(\frac{\Omega^2 r^2}{2} \right) - \frac{dV^2}{2}$$

$$Since,\ Tds = dh - dP/\rho$$

$$\frac{dP}{\rho} = d\left(\frac{\Omega^2 r^2}{2} \right) - \frac{dV^2}{2} - Tds$$

For an isentropic flow, $\frac{dP}{\rho} = d\left(\frac{\Omega^2 r^2}{2} \right) - d\left(\frac{V^2}{2} \right)$

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Centrifugal compressor stage

- For axial compressors, dr≈0 and the above equation reduces to $dP/\rho = -d(V^2/2)$
- Thus in an axial compressor rotor, pressure rise can be obtained only be decelerating the flow.
- In a centrifugal compressor, the term $d(\Omega^2 r^2/2) > 0$, means that pressure rise can be obtained even without any change in the relative velocity.
- With no change in relative velocity, these rotors are not liable to flow separation.

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Centrifugal compressor stage

- However most centrifugal compressors do have deceleration and hence are liable to boundary layer separation,
- Centrifugal compressor rotor is not essentially limited by separation the way axial compressor is.
- It is therefore possible to obtain higher per stage pressure rise from a centrifugal compressor as compared to axial flow compressors.

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Impeller

- In principle, there are three possibilities for a centrifugal compressor rotor.
  - Straight radial
  - Forward leaning
  - Backward leaning
- Forward leaning blades are not used due inherent dynamic instability.
- Straight and backward leaning blades are commonly used in modern centrifugal compressor rotors.

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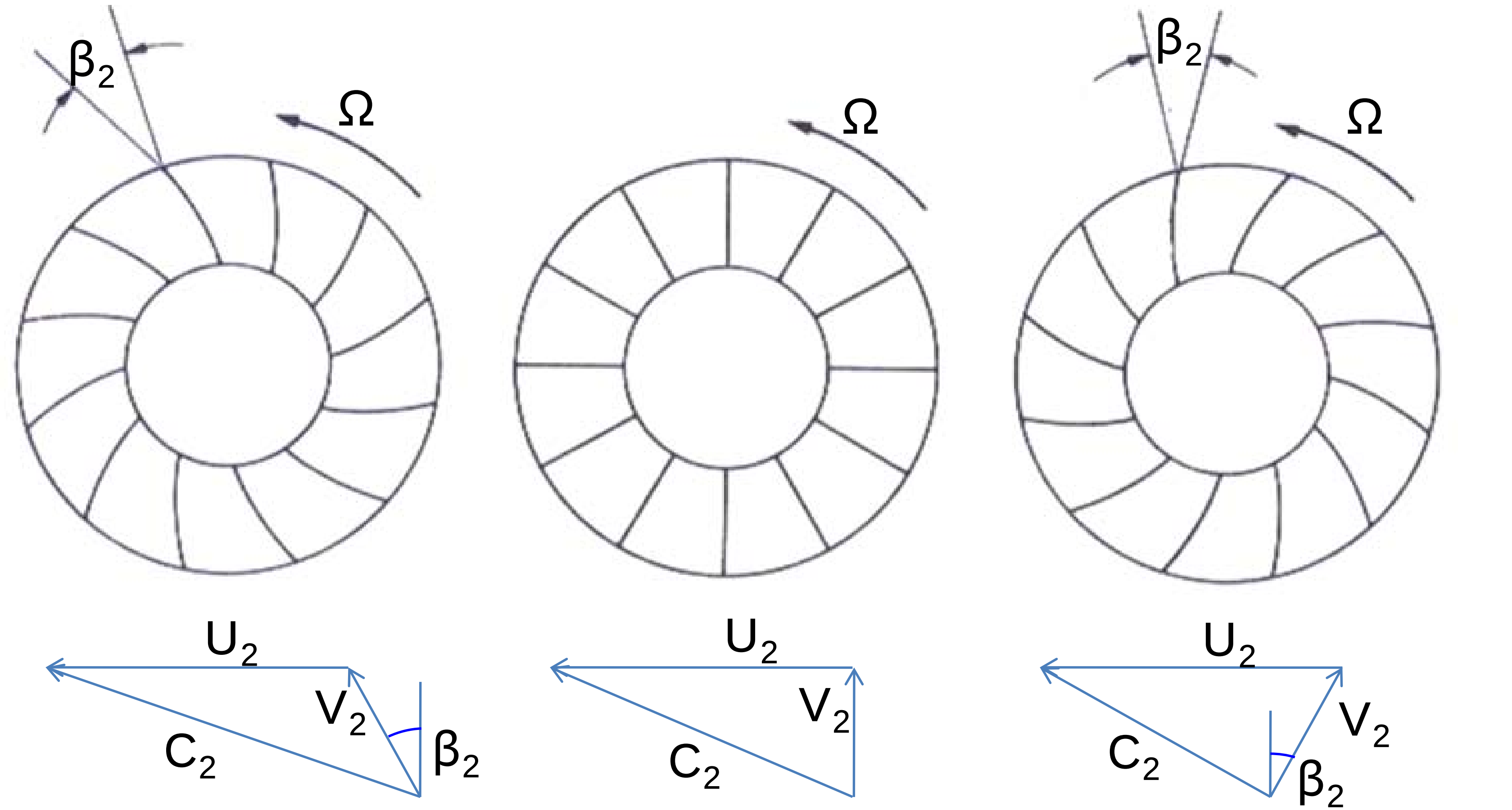
Impeller



Forward leaning blades (β_2 is negative)

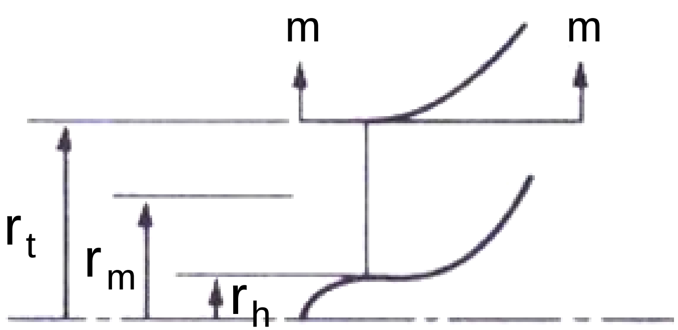
Straight radial

Backward leaning blades (β_2 is positive)

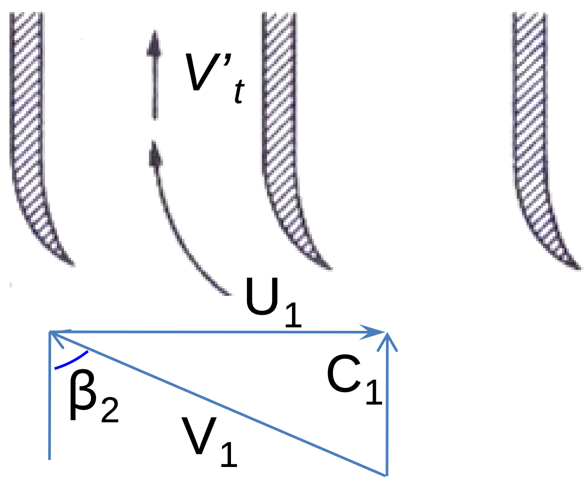
Inducer

- Inducer is the impeller entrance section where the tangential motion of the fluid is changed in the radial direction.
- This may occur with a little or no acceleration.
- Inducer ensures that the flow enters the impeller smoothly.
- Without inducers, the rotor operation would suffer from flow separation and high noise.

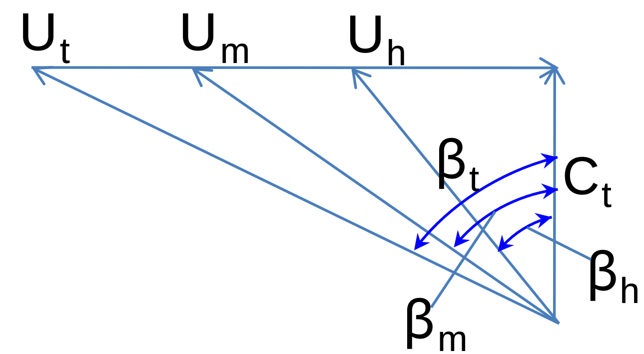
Inducer



Inducer



Section m-m



Leading edge velocity triangles

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Inducer

- It can be seen from the above that
  $V_t^{'} = V_{1t} \cos \beta_{1t}$

  Where, $V^{'}$ denotes the relative velocity at the inducer outlet.
- It can be seen that $V^{'} < V_1$, which indicates diffusion in the inducer.
- Similarly, we can see that the relative Mach number from the velocity triangle is,

$$M_{1rel} = M_1 / \cos \beta_{1t}$$

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Coriolis acceleration

- We have discussed earlier that pressure change due to the centrifugal force field is not a cause of boundary layer separation.
- This can also be explained by the Coriolis forces that are present in centrifugal compressor rotors.
- Let us consider a fluid element travelling radially outward in the passage of a rotor.
- We shall examine the velocity triangles of this fluid during a time period *dt.*

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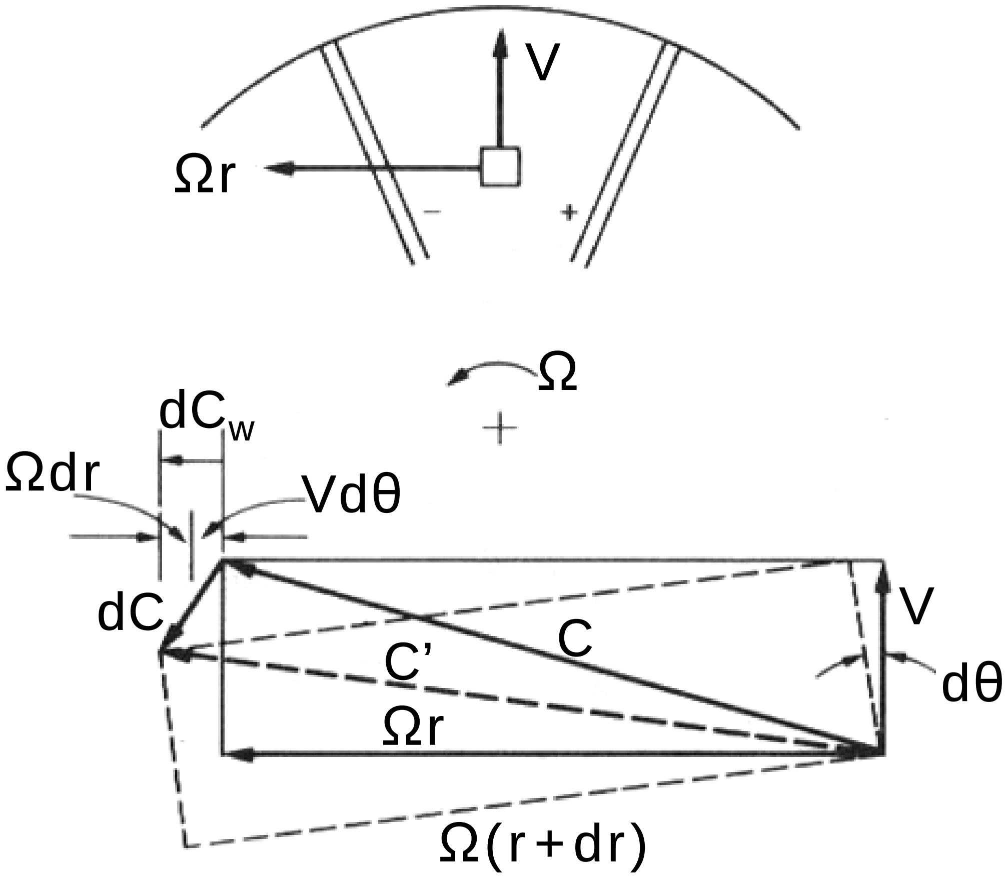
Coriolis acceleration



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Coriolis acceleration

- The magnitude of the relative velocity is unchanged, but the particle has suffered an absolute change of velocity.

$$dV_w = \Omega dr + V d\theta$$

$$or,\ dV_w = \Omega V dt + V\Omega dt,$$

Thus, the Coriolis acceleration , $a_\theta = 2\Omega V$

and it requires a pressure gradient in the tangential

direction of magnitude, $\frac{1}{r}\frac{\partial P}{\partial \theta} = -2\rho\Omega V$

Coriolis acceleration

- The existence of the tangential pressure gradient means that there will be a positive gradient of V in the tangential direction.

$$\frac{1}{\rho}\frac{dP}{rd\theta}=-\frac{d\left(V^2/2\right)}{rd\theta}=-\frac{V}{r}\frac{dV}{d\theta}$$

$$\text{Therefore,}\frac{1}{r}\frac{dV}{d\theta}=2\Omega$$

- This means that there will be a tangential variation in relative velocity.

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Slip factor

- Towards the outlet of the impeller, as the Coriolis pressure gradient disappears, there will be a difference between V_{w2} and U_2.
- This difference in the velocities is expressed as slip factor, $\sigma_s = V_{w2} / U_2$
- The slip factor is approximately related to the number of blades of the impeller.
- For a straight radial blade, the slip factor is empirically expressed as $\sigma_s \approx 1 - 2/N$, where N is the number of blades.

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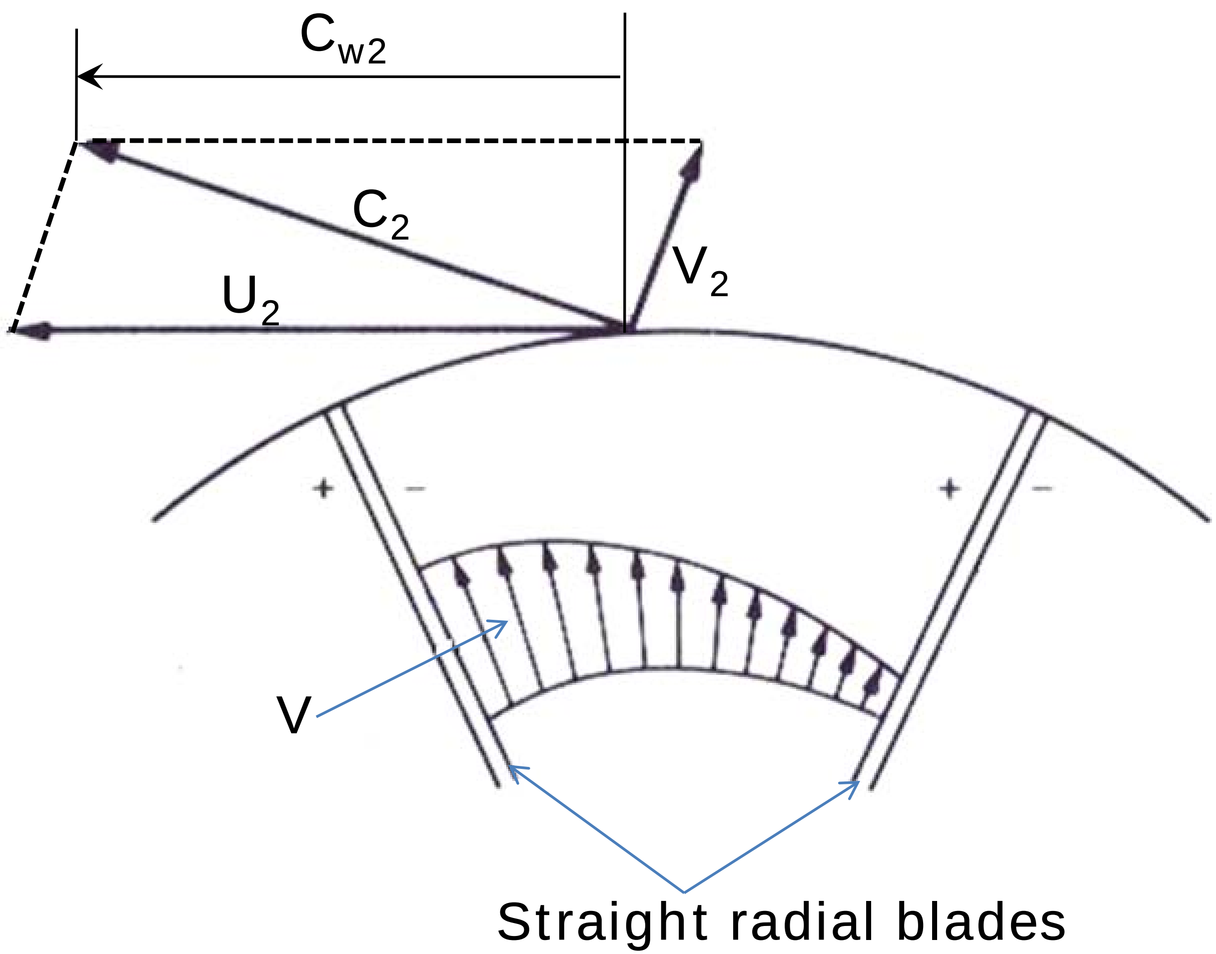
Coriolis acceleration



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The diffuser

- High impeller speed results in a high absolute Mach number leaving the impeller.
- This high velocity is reduced (with an increase in pressure) in a diffuser.
- The fluid flows radially outwards from the impeller, through a vaneless region and then through a vaned diffuser.
- Both vaned and the vaneless diffusers are controlled by boundary layer behaviour.

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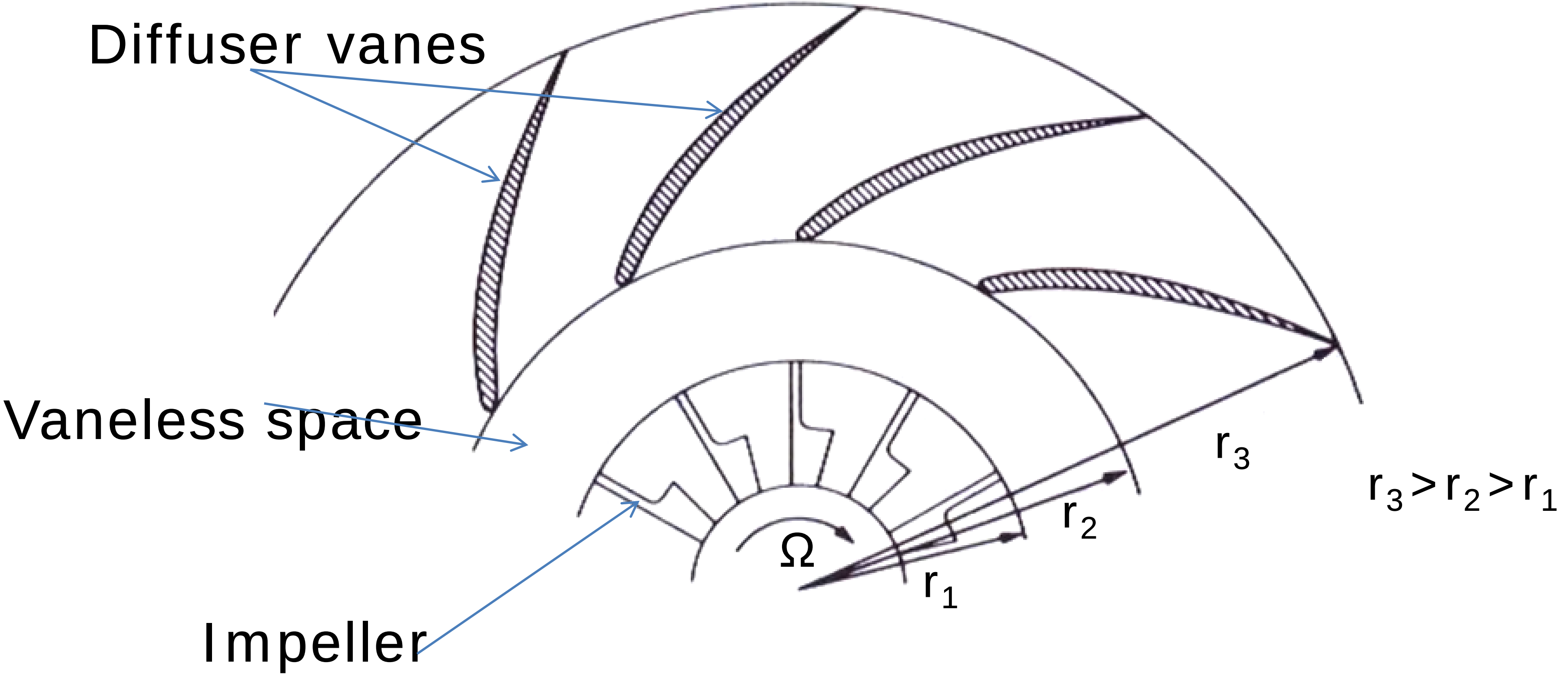
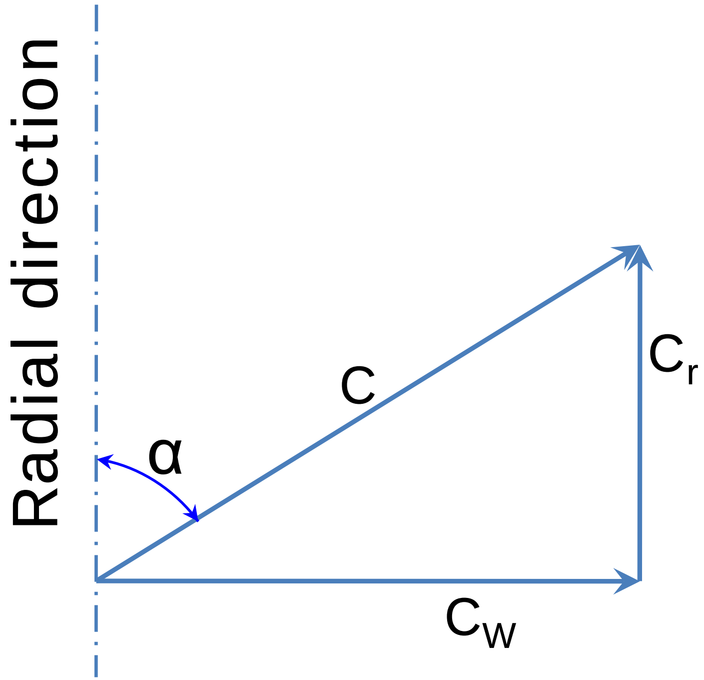
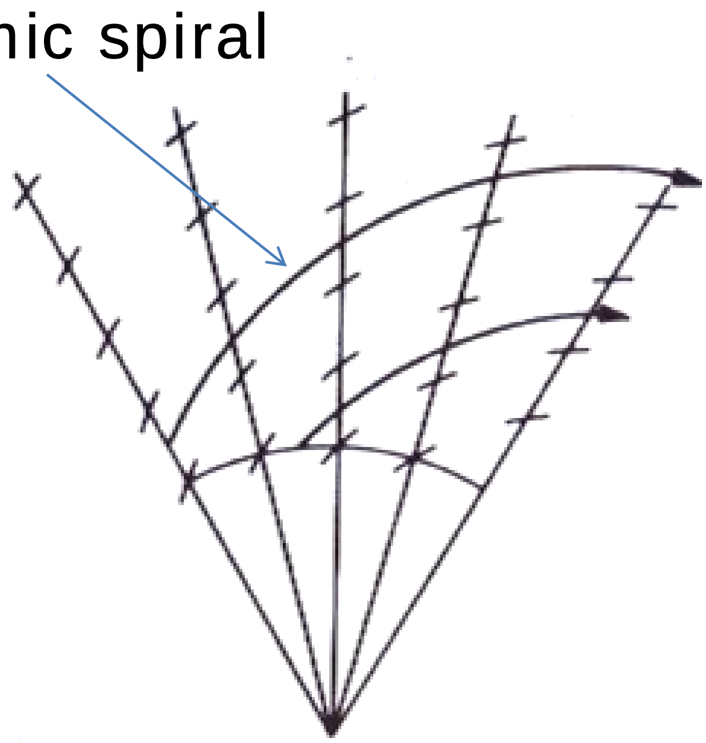
The diffuser



The diffuser





Streamlines in a radial diffuser

The diffuser

Let us consider an incompressible flow in a vaneless region of constant axial width.

From continuity, $\dot{m} = \rho(2\pi rh)C_r = \text{constant}.$

From conservation of angular momentum,

$rC_w = \text{constant}$

$\therefore C_w/C_r = \text{constant} = \tan\alpha$, where α is the angle between the velocity and the radial direction.

Thus, the velocity is inversely proportional to radius. This means that there is diffusion taking place in the vaneless space.

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In the next lecture…

- Performance characteristics of centrifugal compressors
- Surging and choking

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