# TURBOMACHINERY AERODYNAMICS

Lect- 31

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# In this lecture...

- Centrifugal compressors
    - Thermodynamics of centrifugal compressors
    - Components of a centrifugal compressor

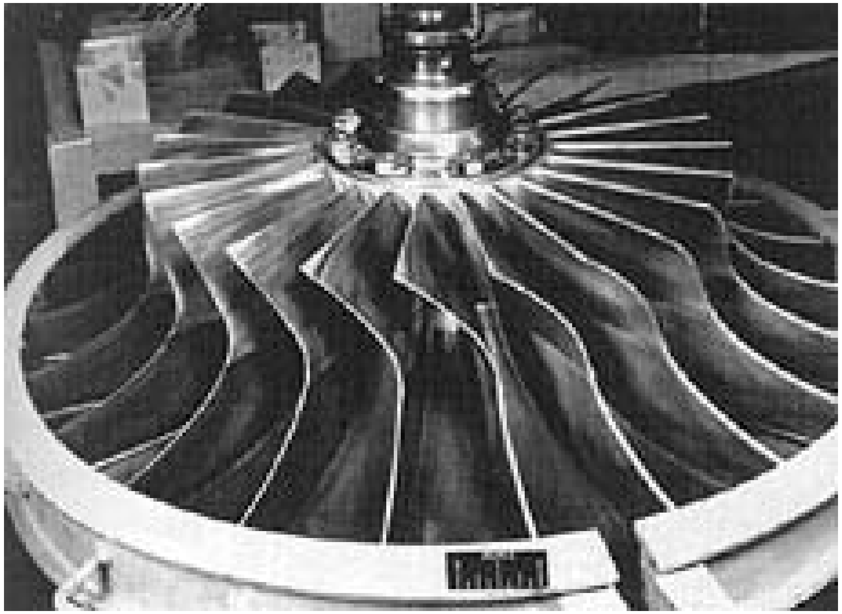
# Centrifugal compressors

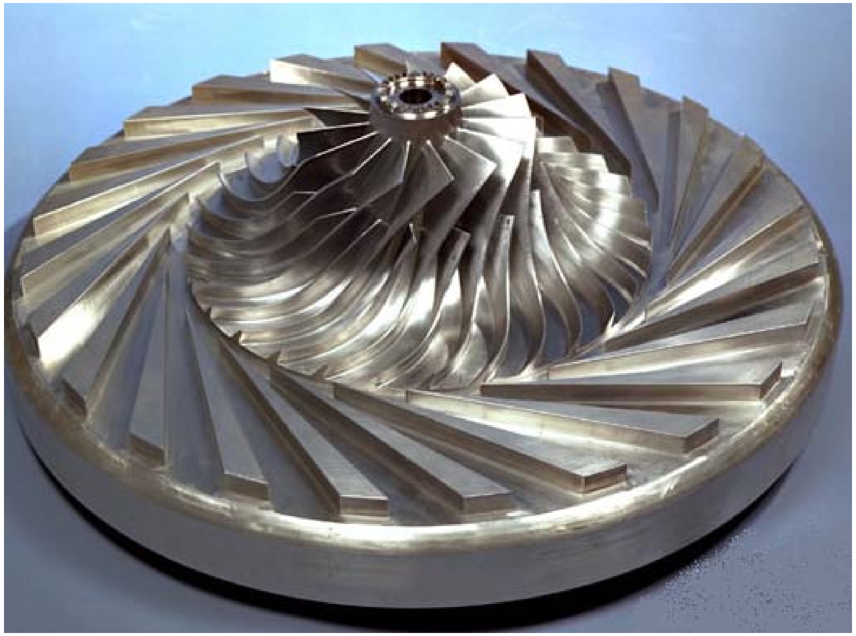
- Centrifugal compressors were used in the first jet engines developed independently by Frank Whittle and Hans Ohain.
- Centrifugal compressors still find use in smaller gas turbine engines.
- For larger engines, axial compressors need lesser frontal area and are more efficient.
- Centrifugal compressors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

# Centrifugal compressors

- Besides small aero engines, centrifugal compressors are used in the auxiliary power units (APUs) in many aircraft.
- Some of the aircraft air conditioning systems employ centrifugal compressors.
- In a few engines, centrifugal compressors are used as the final stage of the compression process downstream of a multi-stage axial compressor. Eg. GE T 700, P&W PT6, Honeywell T53.

# Centrifugal compressors stage





Typical centrifugal compressor rotors



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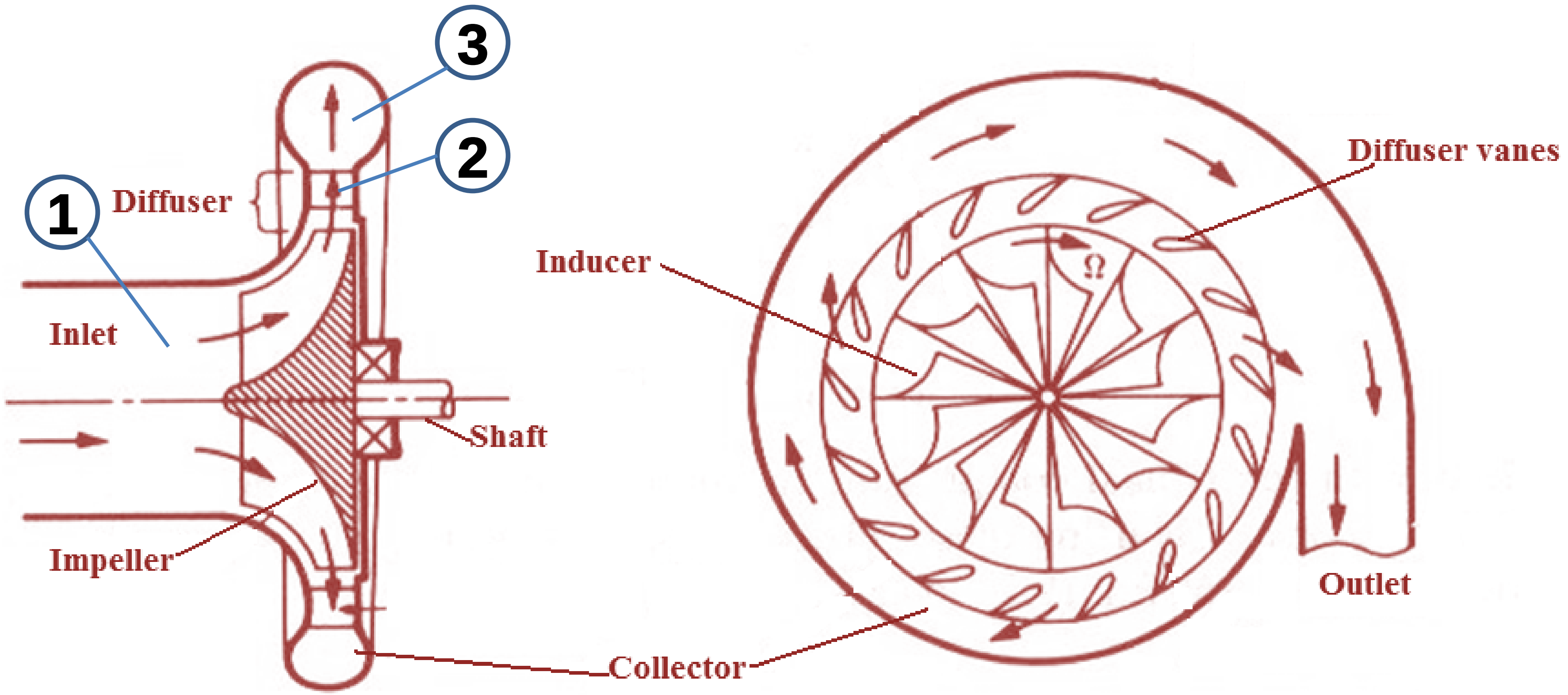
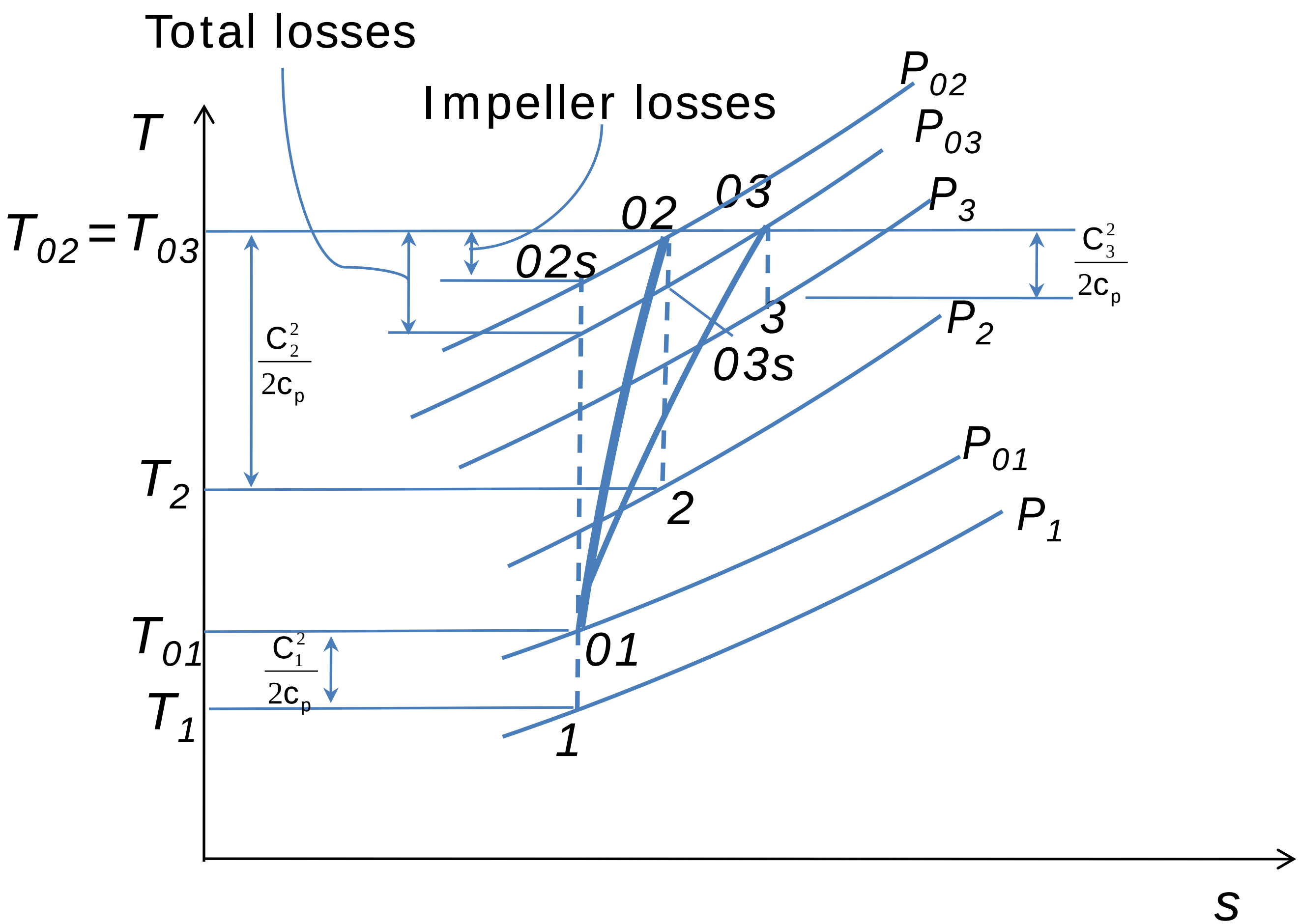
# Centrifugal compressors stage




Schematic of a typical centrifugal compressor

# Centrifugal compressors stage




T-s diagram for a centrifugal compressor

# Centrifugal compressors 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,

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

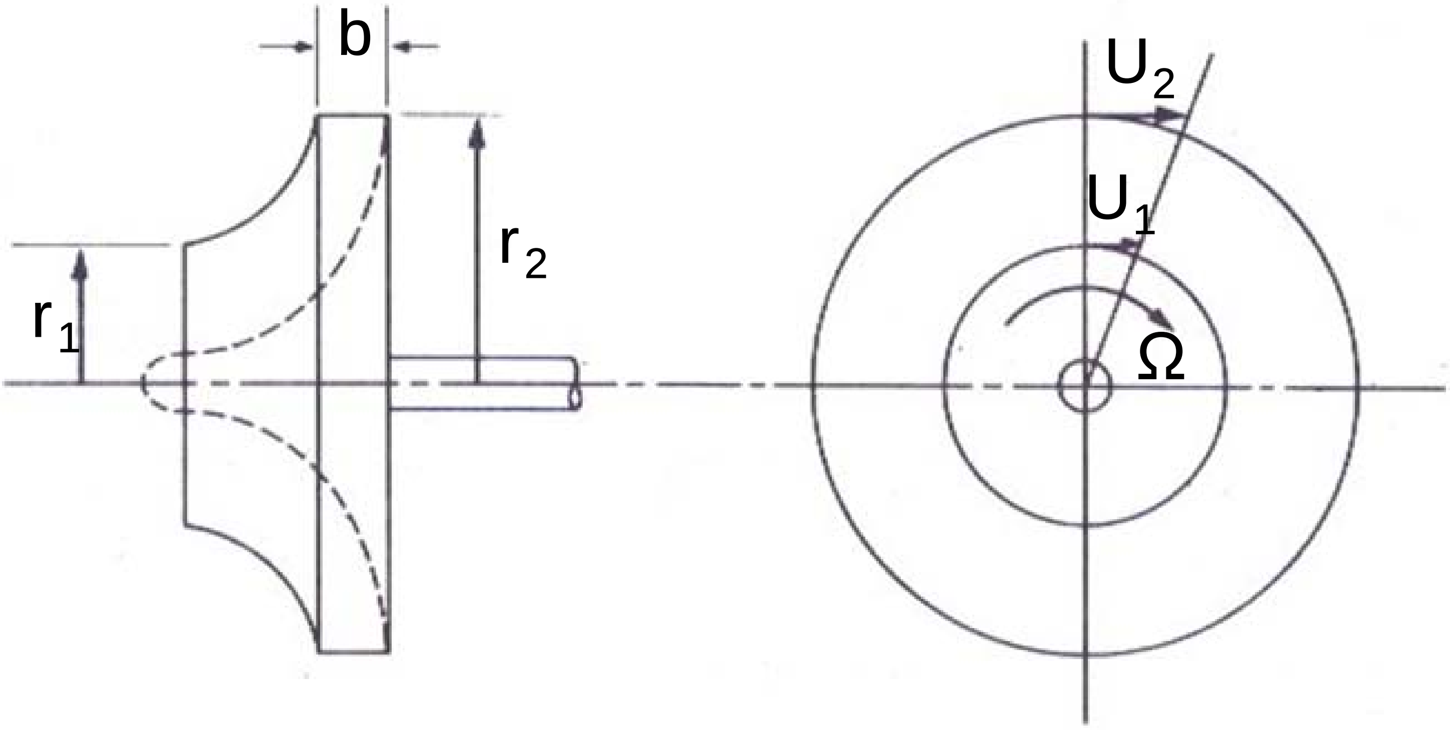
or, $w = (UC_w)_2 - (UC_w)_1$ in which, $U = \Omega r$

From the steady flow energy equation,

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

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

# Centrifugal compressors stage



# Centrifugal compressors stage

The above equation gets transformed to,

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

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

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, $\dfrac{dP}{\rho} = d\left(\dfrac{\Omega^2 r^2}{2}\right) - d\left(\dfrac{V^2}{2}\right)$

# Centrifugal compressors stage

- For axial compressors, $dr \approx 0$ 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.

# Centrifugal compressors 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.

# Conservation of Rothalpy

- If we were to assume steady, viscous flow without heat transfer

$$h_1 + \frac{C_1^2}{2} - U_1C_{w1} = h_2 + \frac{C_2^2}{2} - U_2C_{w2} = I$$

- Here, I, is the rotational enthalpy or rothalpy.
- It is now known that rothalpy is conserved for the flow through the impeller.
- Any change in rothalpy is due to the fluid friction acting on the stationary shroud (if considered in the analysis).

# Impeller

- Impeller draws in the working fluid. It is the rotating component of the centrifugal compressor.
- The diverging passages of the impeller diffuses the flow to a lower relative velocity and higher static pressure.
- Impellers may be single-sided or double-sided, shrouded or un-shrouded.
- In the impeller, the working fluid also experiences centripetal forces due to the rotation.

# 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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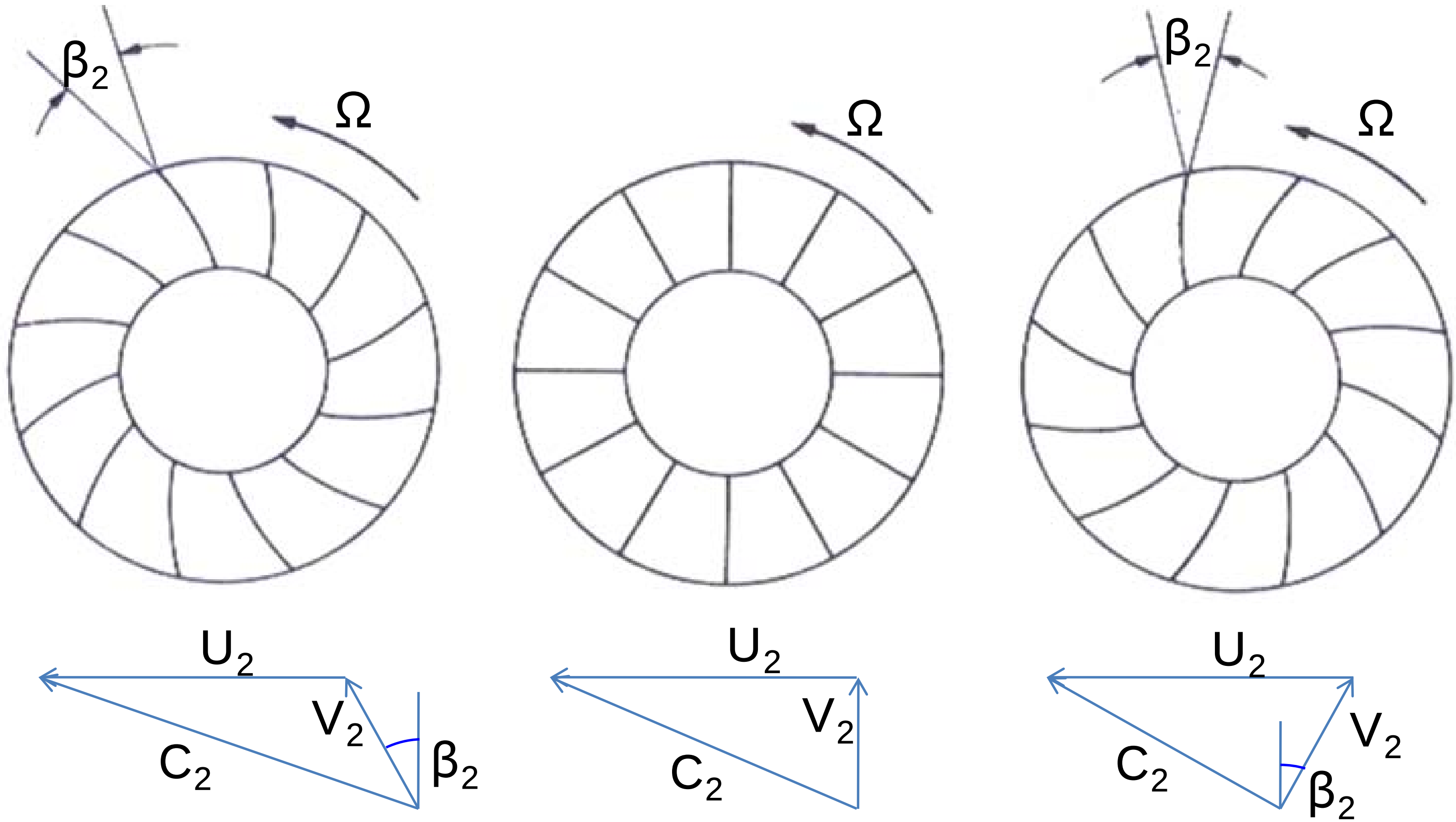
# Impeller




Forward leaning blades ($\beta_2$ is negative)

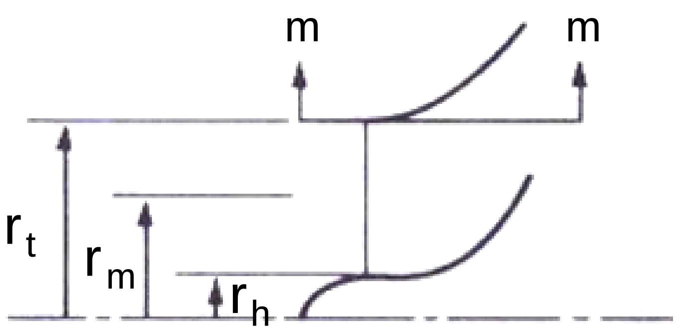
Straight radial

Backward leaning blades ($\beta_2$ is positive)

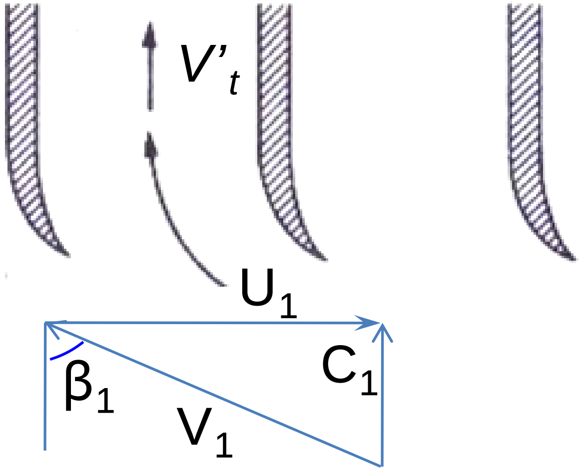
# Inducer

- 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.

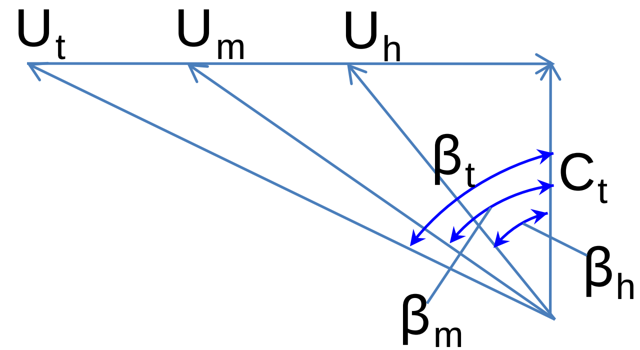
# Inducer




Inducer




Section m-m




Leading edge velocity triangles

# 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,

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

# 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.
- Diffuser represents the fixed or stationary part of the compressor.
- The diffuser decelerates the flow exiting the impeller and thus reduces the absolute velocity of the working fluid.
- The amount of deceleration depends upon the efficiency of the diffusion process.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# The 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.
- Pipe and channel type diffusers are used in aero engines due to their compatibility with the combustors.


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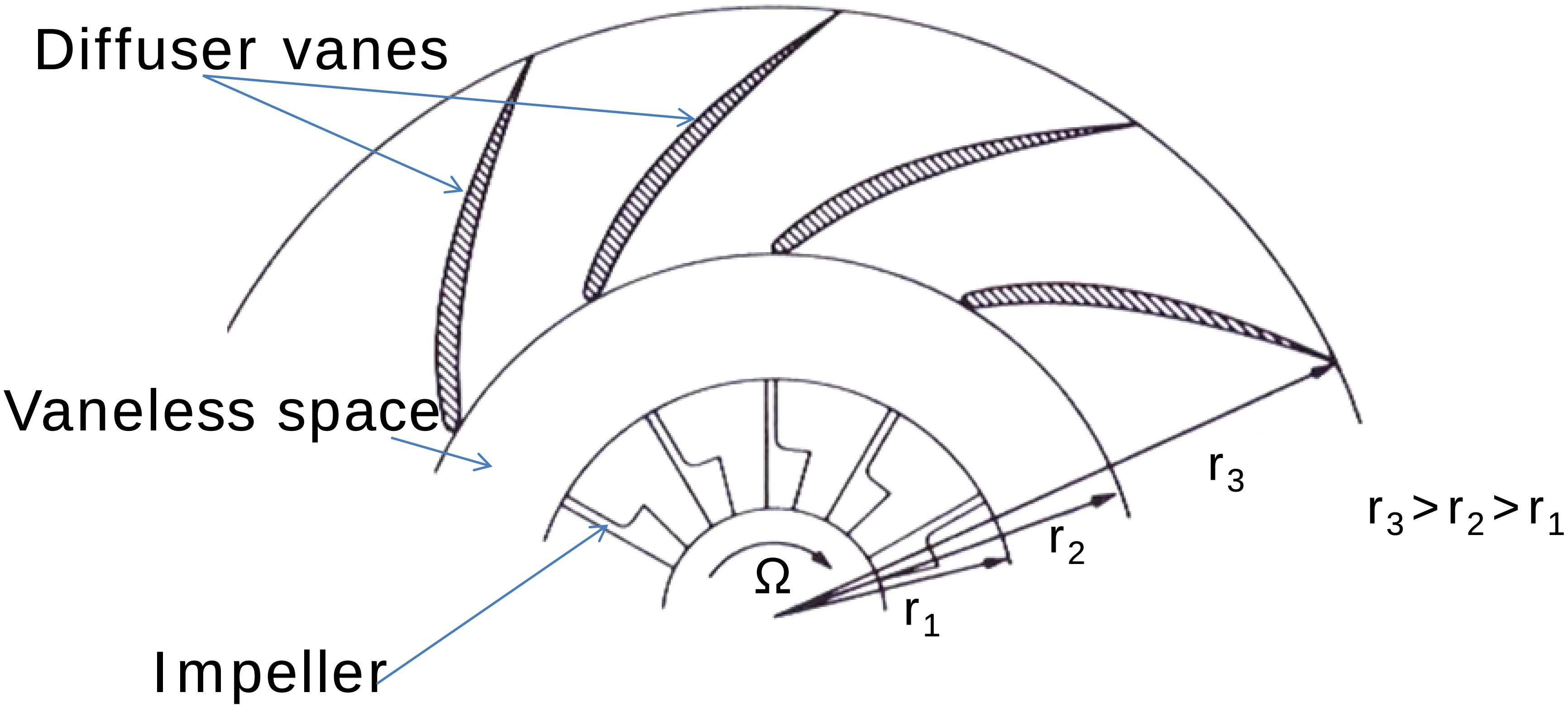
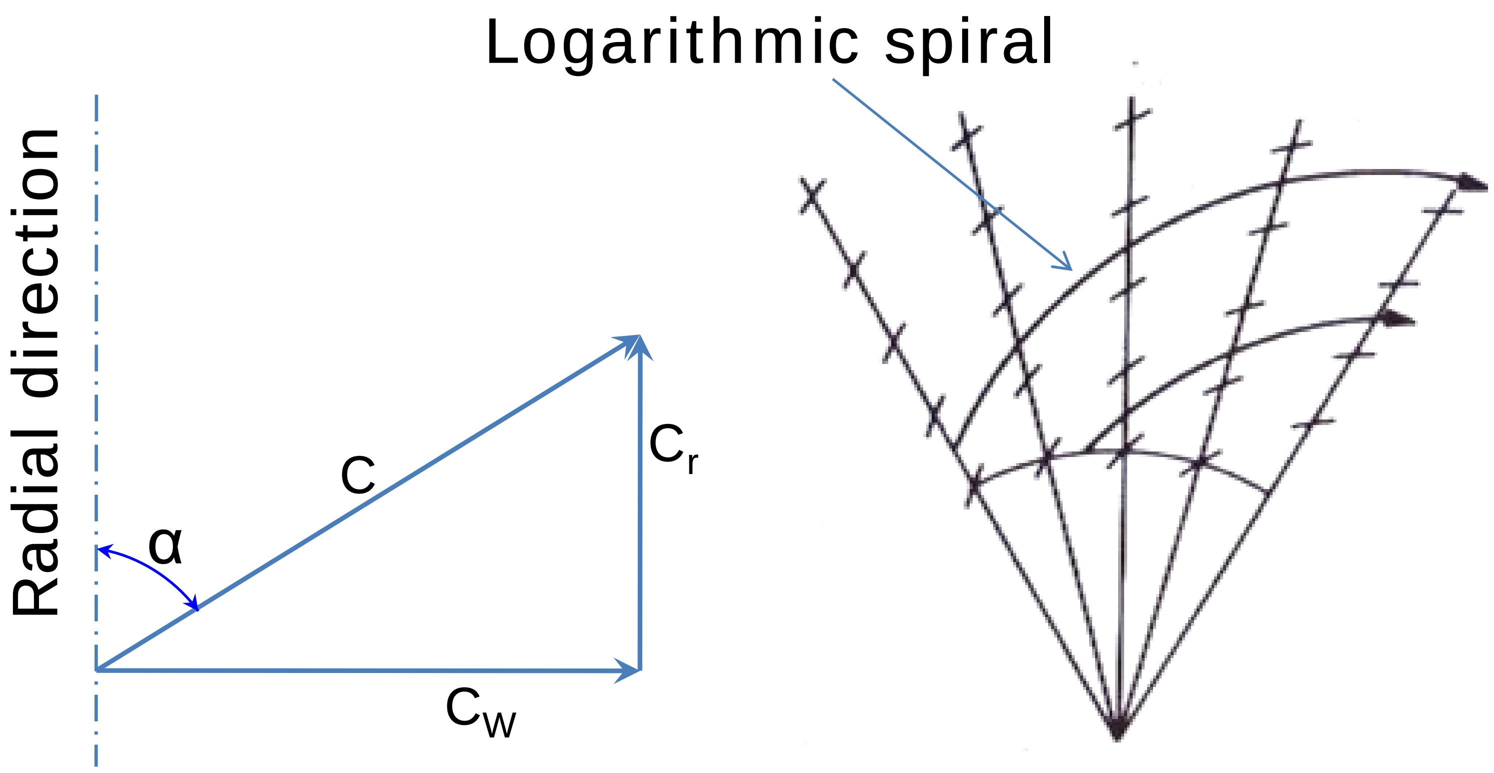
# The diffuser



# 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 $\alpha$ 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.

# In the next lecture...

- Centrifugal compressors
  - Coriolis acceleration
  - Slip factor
  - Performance characteristics
  - Stall and surge

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- Centrifugal compressors
  - Thermodynamics of centrifugal compressors
  - Components of a centrifugal compressor