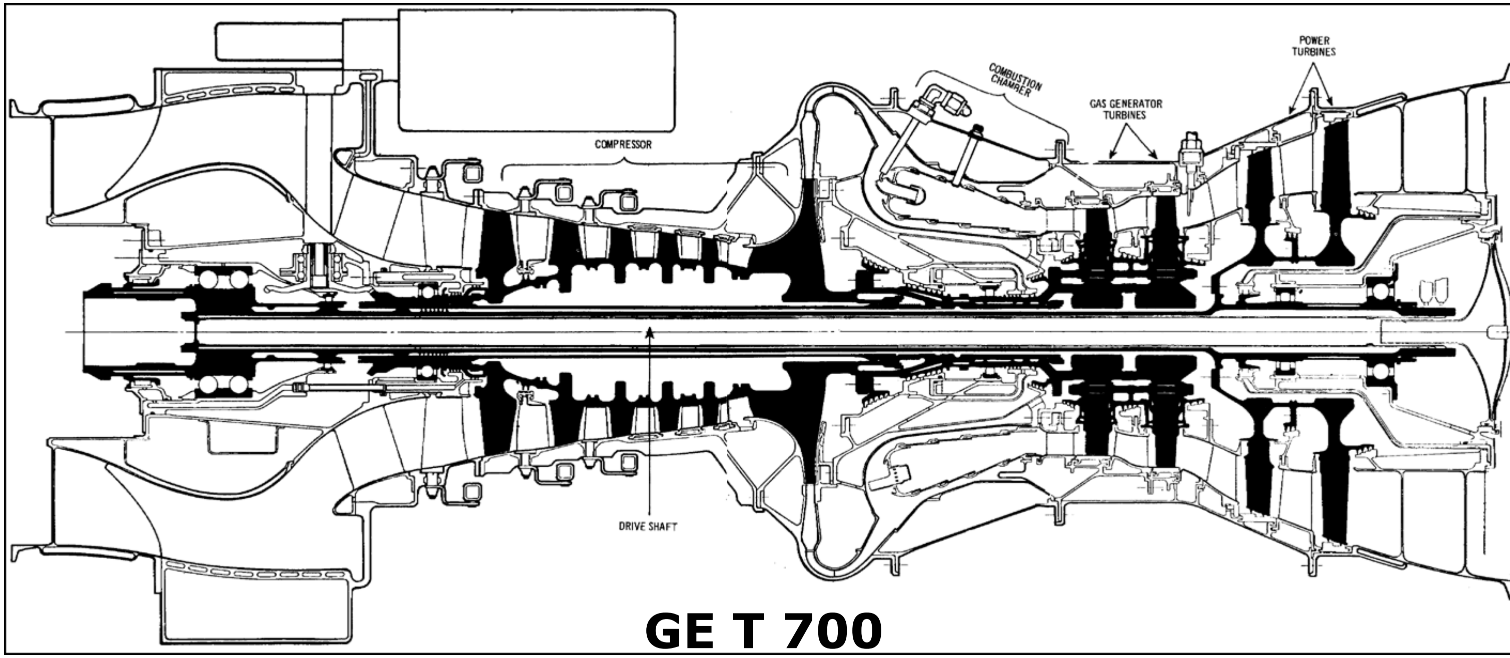
- Recap: Lecture 20, 13th October 2015, 1530-1655 hrs.
  - Turbine blade cooling requirements
  - History of turbine blade cooling
  - Types of turbine blade cooling
  - Turbine blade materials
  - Cooling passage management

Centrifugal compressors

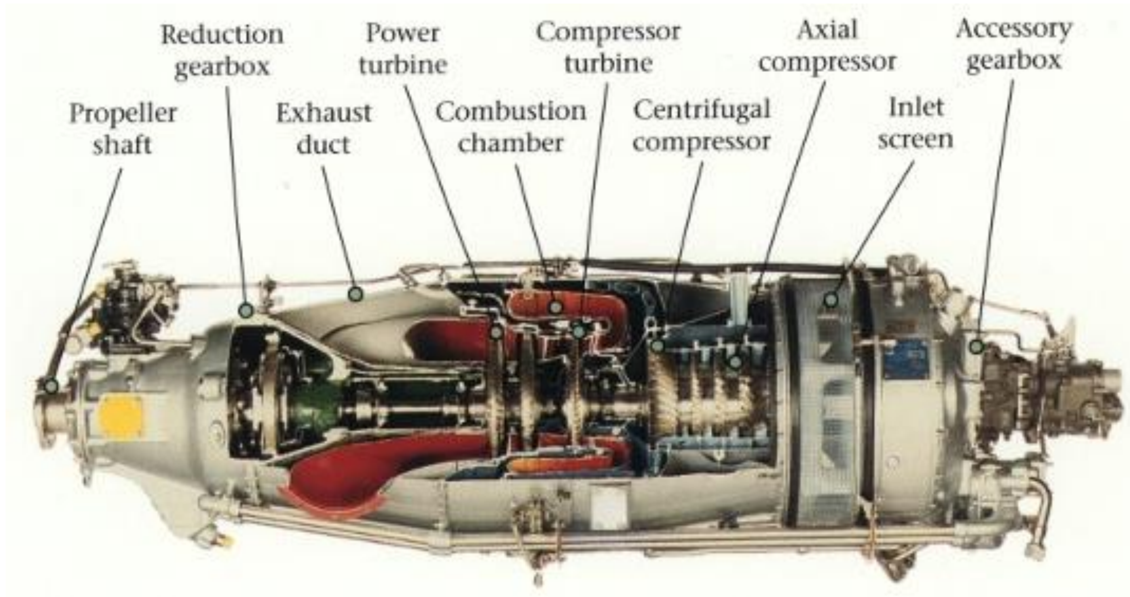
- Centrifugal compressors were used in the first jet engines developed independently by Frank Whittle and Hans Ohain.
- Centrifugal compressors still find use in smaller gas turbine engines.
- For larger engines, axial compressors need lesser frontal area and are more efficient.
- Centrifugal compressors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

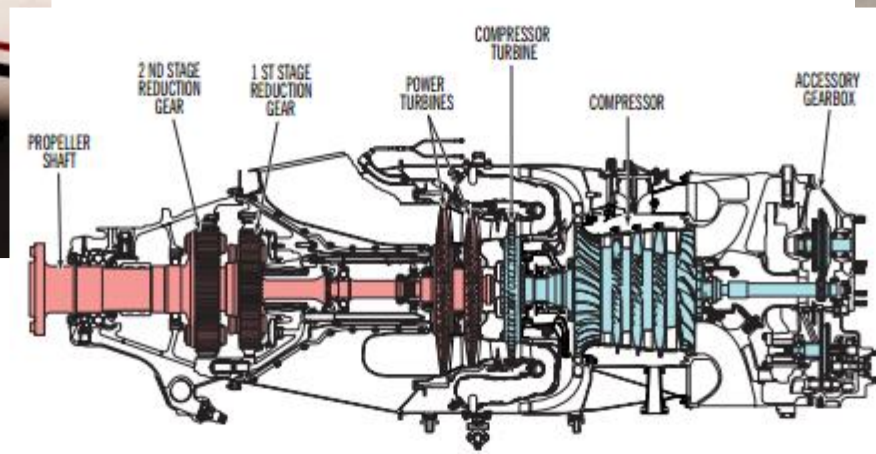


GE T 700

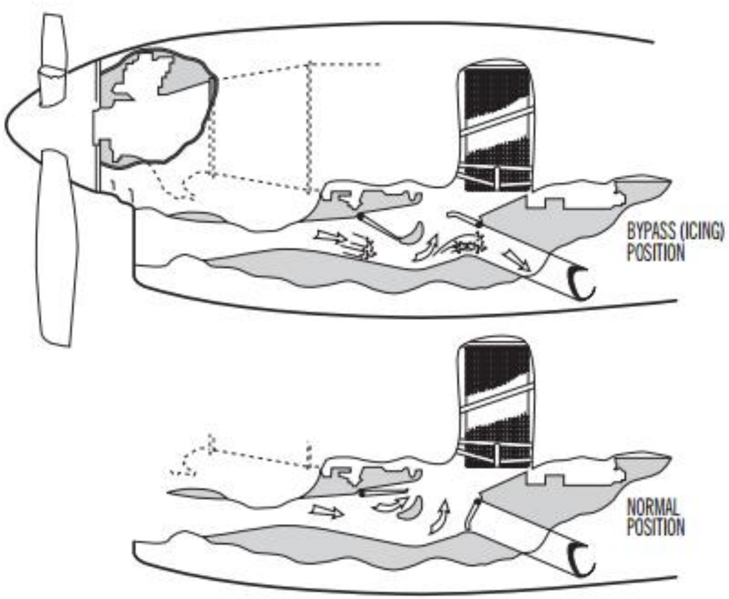


P&W PT6

PT6: Turboprop Engine



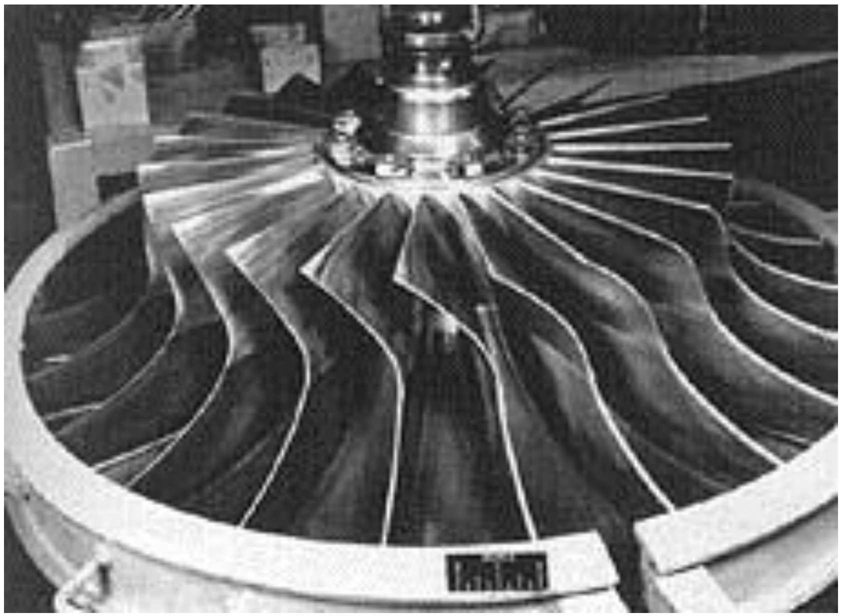
Large PT6A Engine



- 500 to 2,000 shaft horsepower class
- Multi- stage axial and single-stage centrifugal compressor
- Reverse flow combustor
- Single-stage compressor turbine
- Independent ‘free’ power turbine with shrouded blades
- Forward facing output for fast hot section refurbishment
- Epicyclic speed reduction gearbox

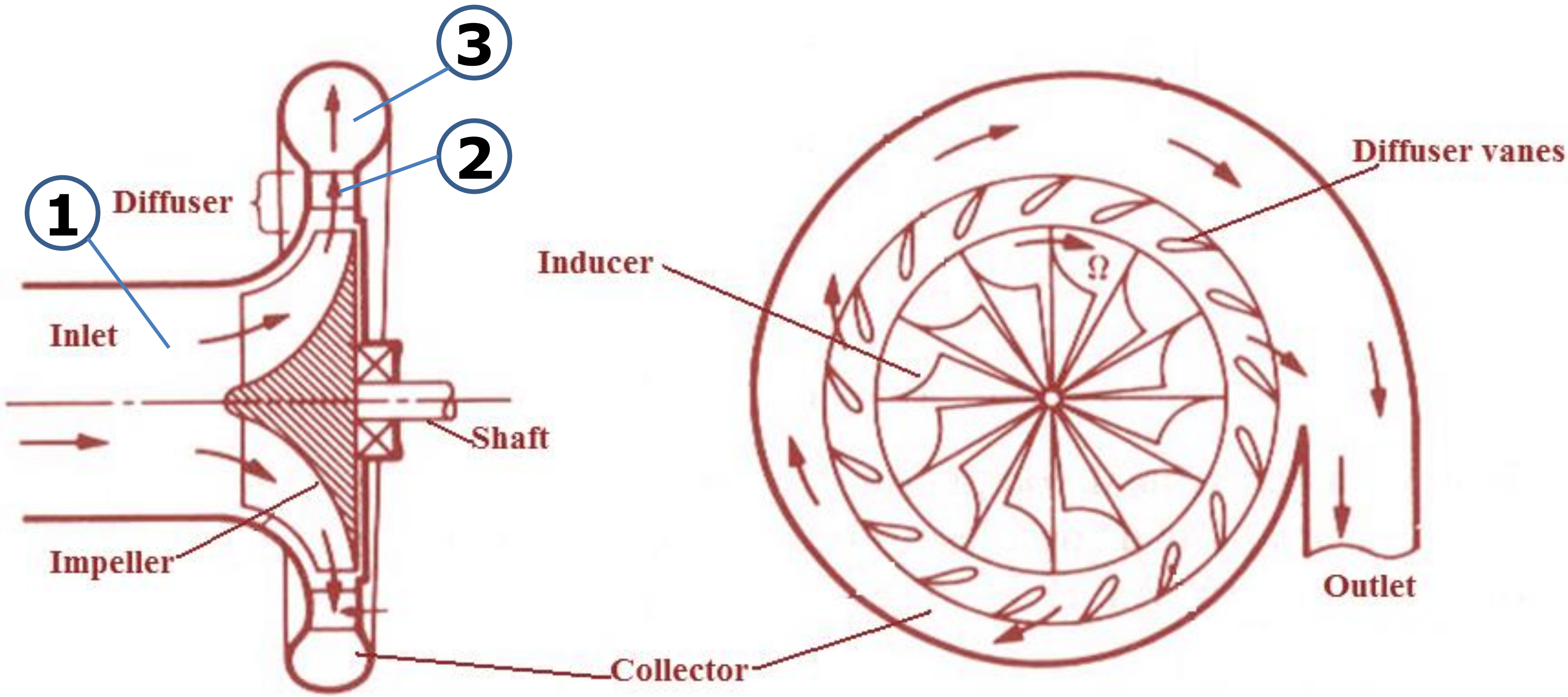
Source: http://www.pwc.ca/en/engines/pt6a

Centrifugal compressor stage

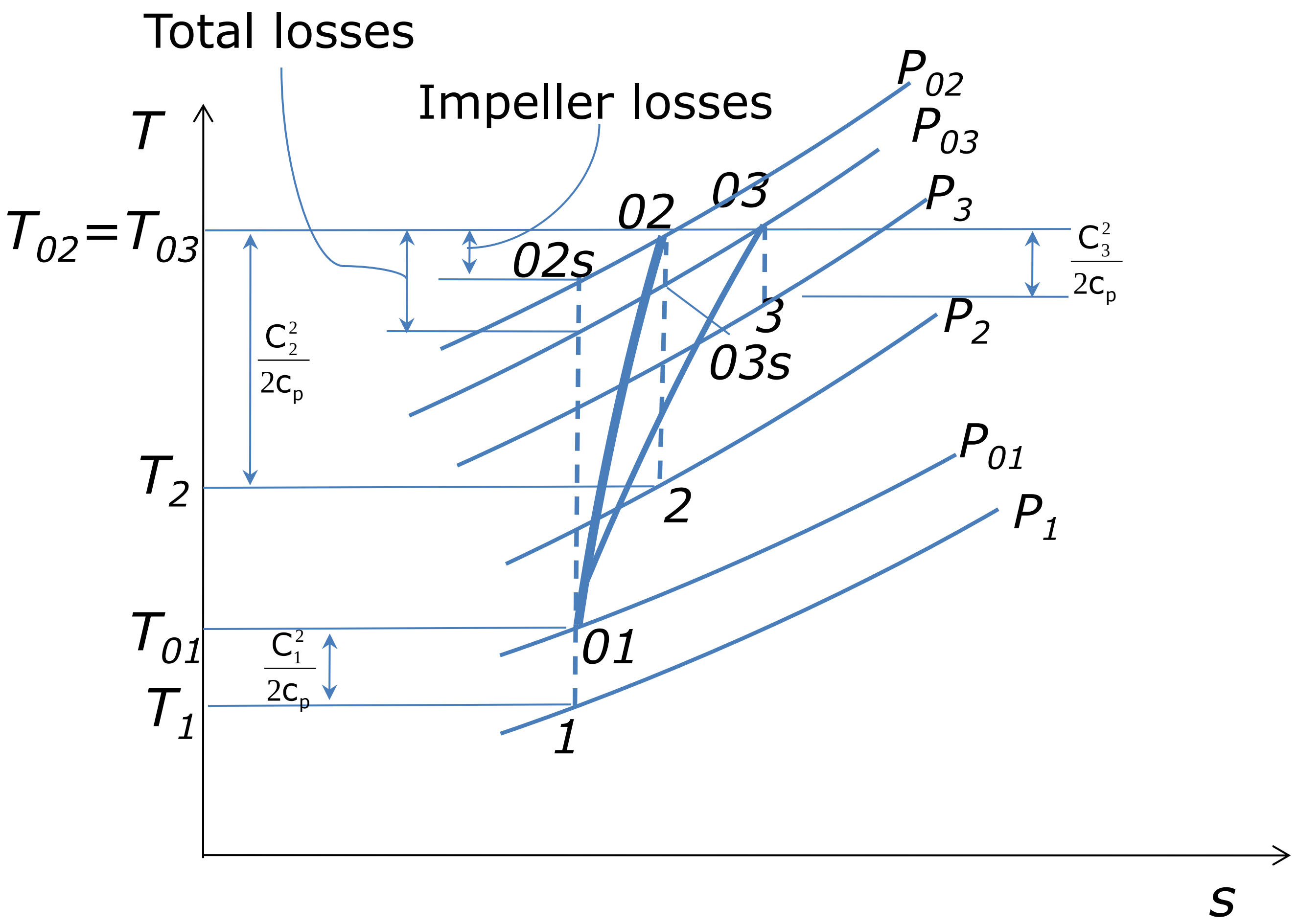
Typical centrifugal compressor rotors

Centrifugal compressor stage



Schematic of a typical centrifugal compressor

Centrifugal compressor stage



T-s diagram for a centrifugal compressor

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,

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

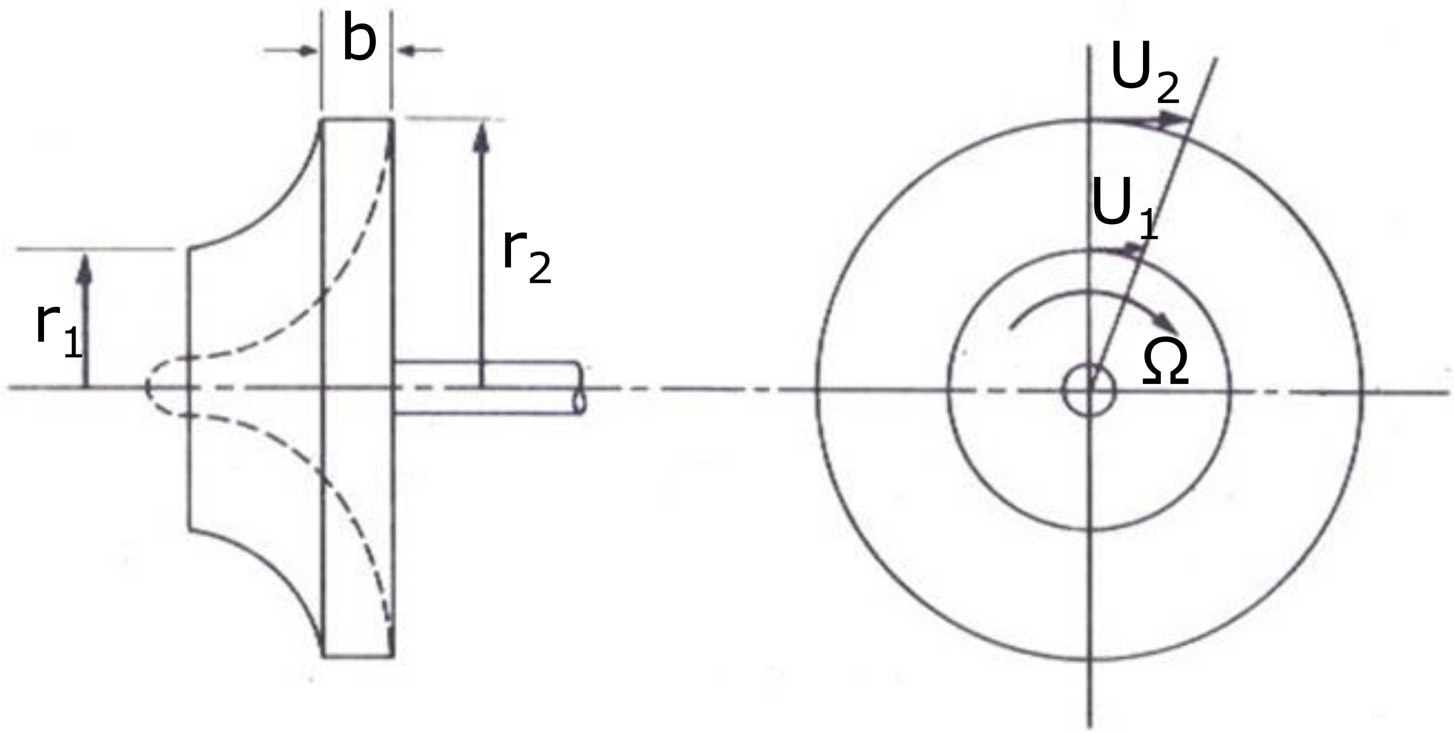
or, $w = (UC_w)_2 - (UC_w)_1$ in which, $U = \Omega r$

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

Centrifugal compressor stage



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

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

Centrifugal compressor 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 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.

Conservation of Rothalpy

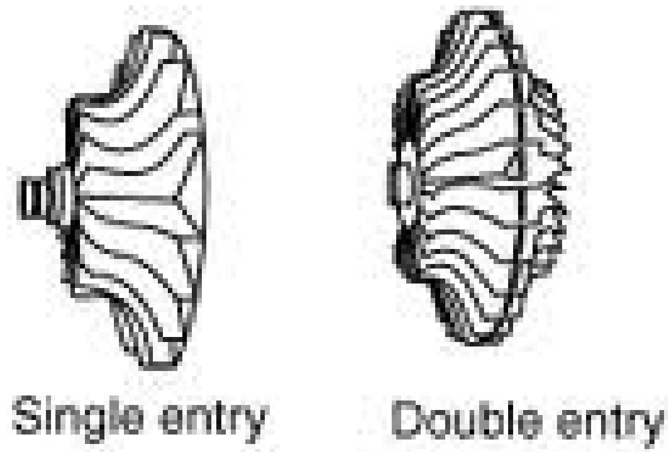
- If we were to assume steady, viscous flow without heat transfer

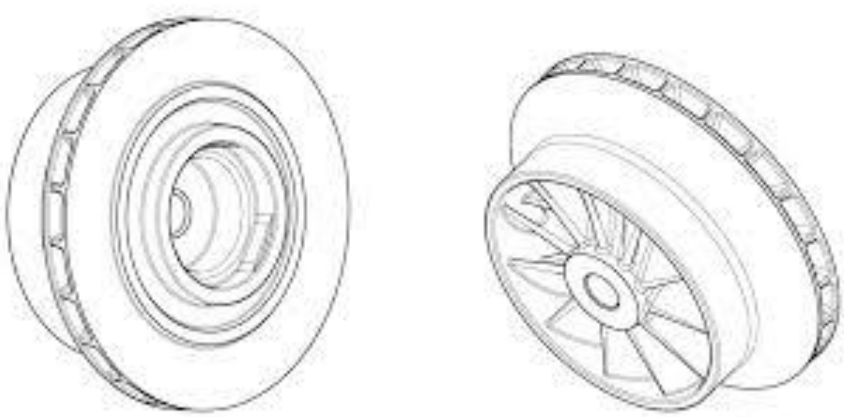
$$h_1 + \frac{C_1^2}{2} - U_1 C_{w1} = h_2 + \frac{C_2^2}{2} - U_2 C_{w2} = I$$

- 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).

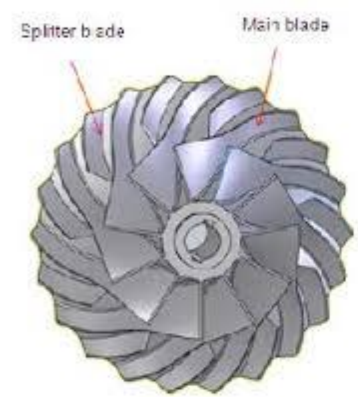
Impeller

- 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.





shrouded impeller

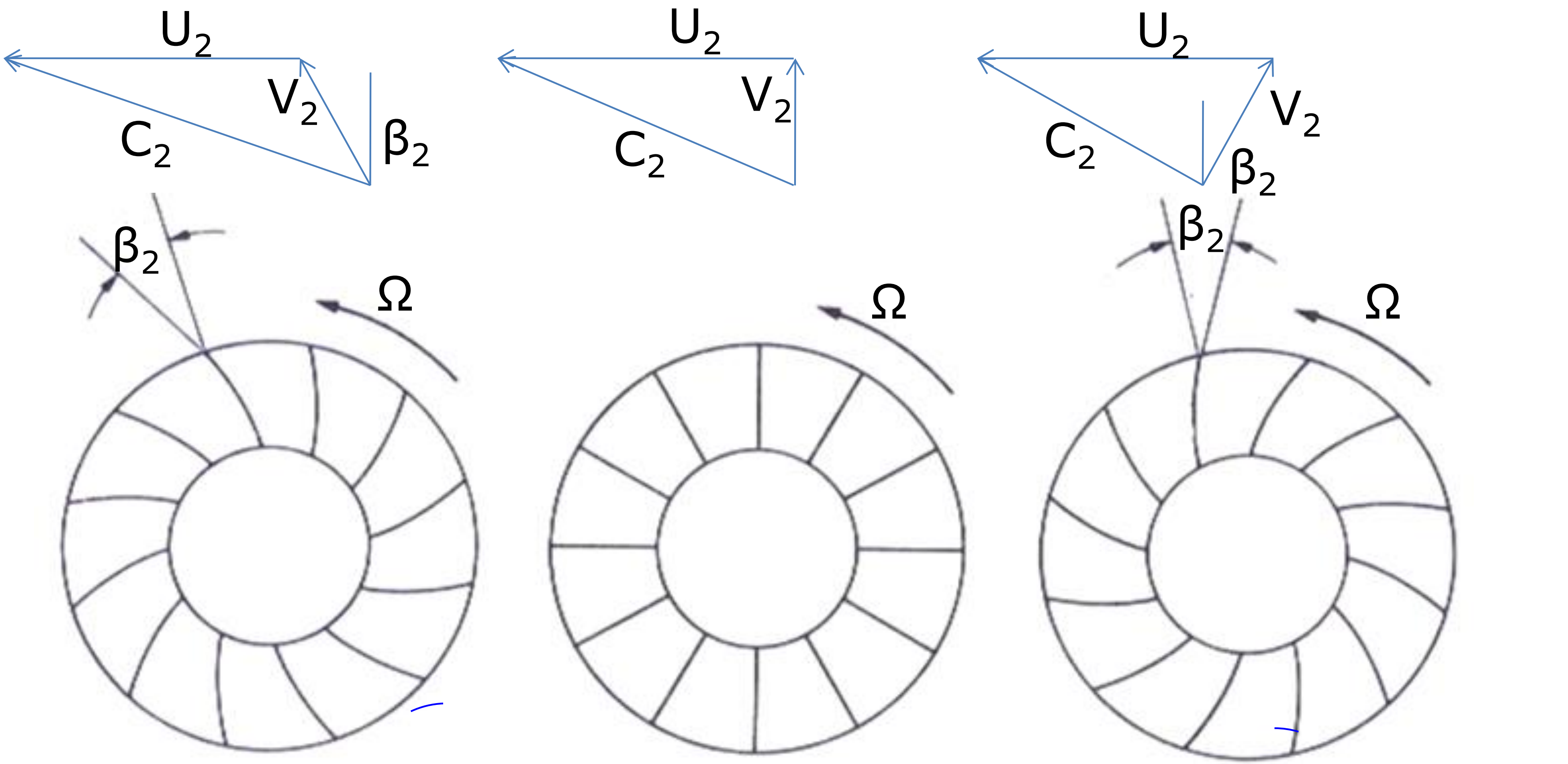


un-shrouded impeller

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.

Impeller



Forward leaning blades (β_2 is negative)

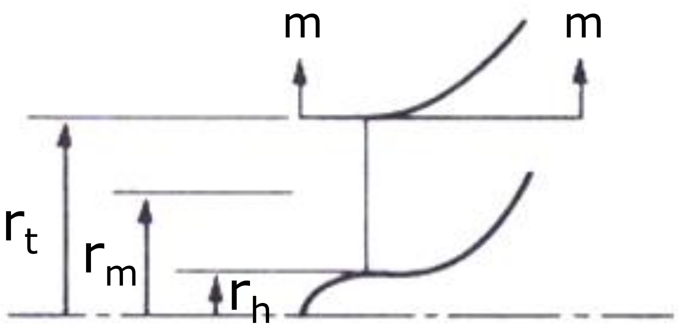
Straight radial

Backward leaning blades (β_2 is positive)

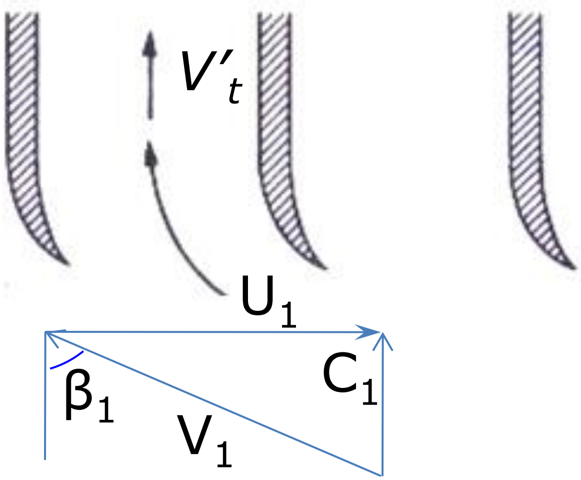
Inducer

- 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.

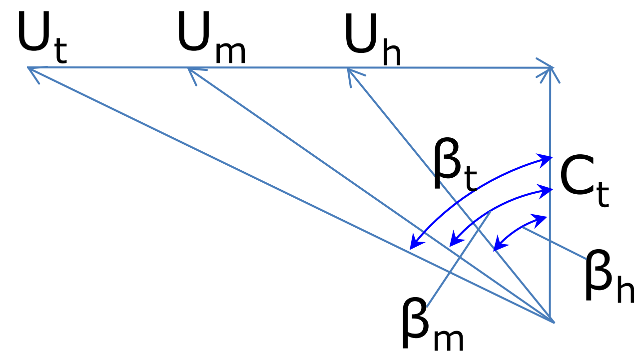
Inducer



Inducer



Section m-m



Leading edge velocity triangles

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,

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