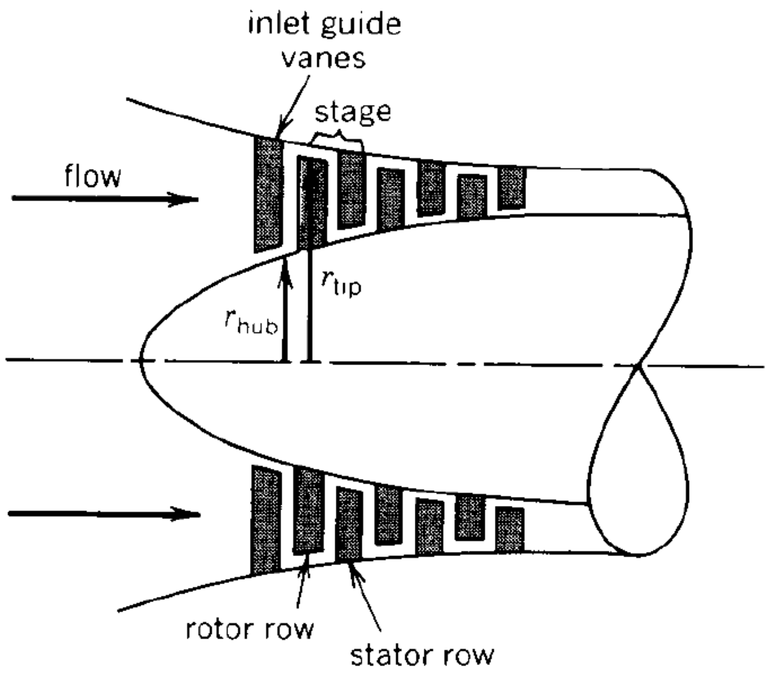
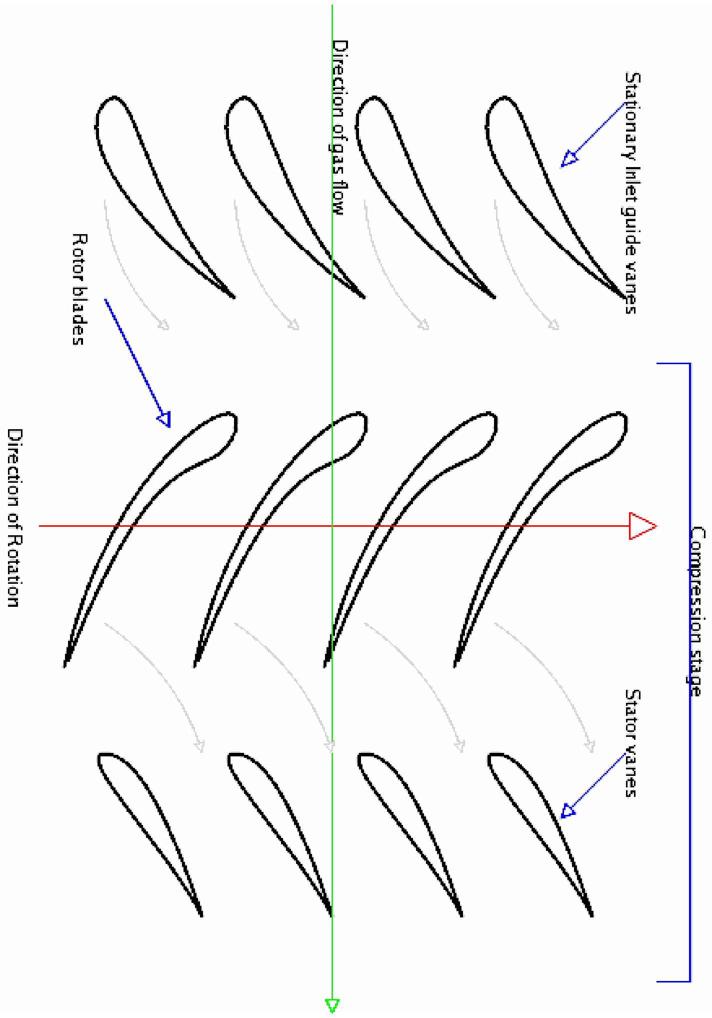
Axial Flow Compressor

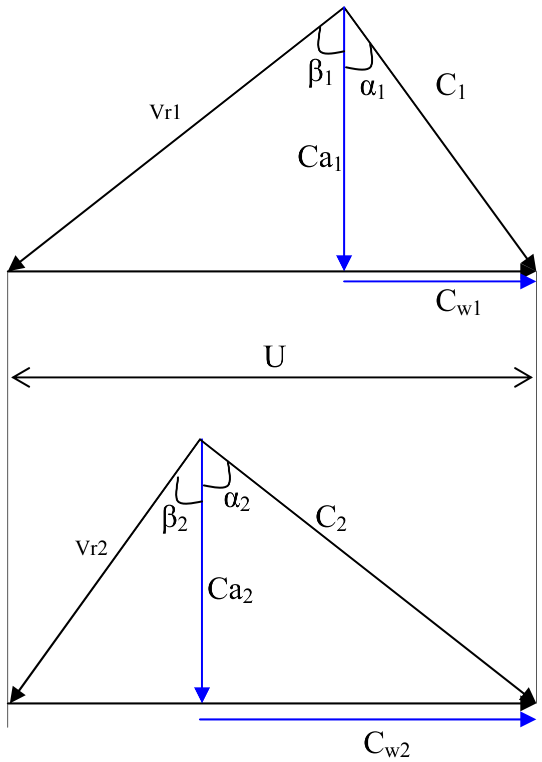
Axial compressors are rotating, airfoil-based compressors in which the working fluid principally flows parallel to the axis of rotation. This is in contrast with other rotating compressors such as centrifugal, axi-centrifugal and mixed-flow compressors where the air may enter axially but will have a significant radial component on exit. Axial flow compressors produce a continuous flow of compressed gas, and have the benefits of high efficiencies and large mass flow capacity, particularly in relation to their cross-section. They do, however, require several rows of airfoils to achieve large pressure rises making them complex and expensive relative to other designs. Axial compressors are widely used in gas turbines, such as jet engines, high speed ship engines, and small scale power stations. They are also used in industrial applications such as large volume air separation plants, blast furnace air, fluid catalytic cracking air, and propane dehydrogenation. Axial compressors, known as superchargers, have also been used to boost the power of automotive reciprocating engines by compressing the intake air, though these are very rare.

Components: Axial compressors consist of rotating and stationary components. A shaft drives a central drum, retained by bearings, which has a number of annular airfoil rows attached. These rotate between a similar number of stationary airfoil rows attached to a stationary tubular casing. The rows alternate between the rotating airfoils (rotors) and stationary airfoils (stators), with the rotors imparting energy into the fluid, and the stators converting the increased rotational kinetic energy into static pressure through diffusion. A pair of rotating and stationary airfoils is called a stage. The cross-sectional area between rotor drum and casing is reduced in the flow direction to maintain axial velocity as the fluid is compressed.

Principle of operation: the compression is fully based on diffusing action of the passages. The main parts include a stationary (stator) part and a moving (rotor) part. The diffusing action in stator converts absolute kinetic head of the fluid into rise in pressure. The relative kinetic head in the energy equation is a term that exists only because of the rotation of the rotor. The rotor reduces the relative kinetic head of the fluid and adds it to the absolute kinetic head of the fluid i.e., the impact of the rotor on the fluid particles increases its velocity (absolute) and thereby reduces the relative velocity between the fluid and the rotor. In short, the rotor increases the absolute velocity of the fluid and the stator converts this into pressure rise. Designing the rotor passage with a diffusing capability can produce a pressure rise in addition to its normal functioning.







The basic two parts are:

Rotor: transfers all the work input to the stage to the air.

Stator: serves to recover as a pressure rise part of the kinetic energy imparted to the working fluid and also to direct the flow into an angle suitable for entry to the next stage.

The two triangles are plotted at the mean blade height where the blade peripheral velocity is U, where:
C: is the absolute velocity
Vr: is the relative velocity
Cw: whirl component of the absolute velocity
Ca: axial component of the absolute velocity
β: Blade angle
α: Air angle

Assumption: The axial velocity is constant through the stage Ca1=Ca2=Ca

$$tan\,\alpha_1 = \frac{C_{w1}}{Ca}$$

$$tan\,\beta_1 = \frac{U - C_{w1}}{Ca}$$

$$\frac{U}{Ca} = tan\,\alpha_1 + tan\,\beta_1 \qquad (1)$$

$$\frac{U}{Ca} = tan\,\alpha_2 + tan\,\beta_2 \qquad (2)$$

$T=m(C_{w2}\,r_m - C_{w1}\,r_m)$

r_m: mean radius

$W=\omega T= Um(C_{w2} - C_{w1})$ Work done

$W=U\,(C_{w2} - C_{w1})$ Work done per unit mass flow or Specific work.

$W=U\,Ca\,(\tan\alpha_2 - \tan\alpha_1)$ (3)
From eq. 1 and 2

$\tan\alpha_2 - \tan\alpha_1 = \tan\beta_1 - \tan\beta_2$

$W=U\,Ca\,(\tan\beta_1 - \tan\beta_2)$ (4)

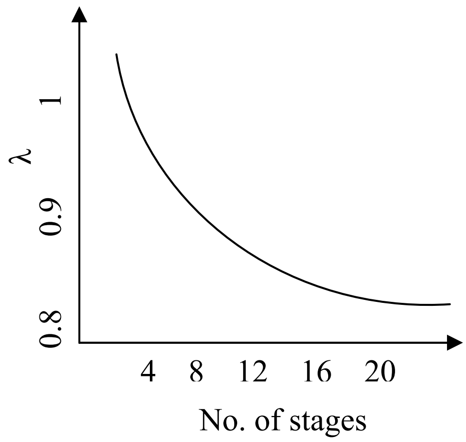
- The input energy will transferred to a rise in stagnation temperature of air ΔT_{os}.
- If C_3 is made equal to C1 $\rightarrow \Delta T_{os} = \Delta T_s$

$$\Delta T_{os} = \Delta T_s = U\,Ca/C_p(\tan\beta_1 - \tan\beta_2) \qquad (5)$$

Due to losses, the specific work calculated from equ. 4 is multiplied by a value less than unity (work done factor) (λ) to obtain the actual work which can be supplied to the stage

$$\Delta T_{os} = (\lambda/C_p)\,U\,Ca\,(\tan\beta_1 - \tan\beta_2)$$

λ varies with the number of stages:



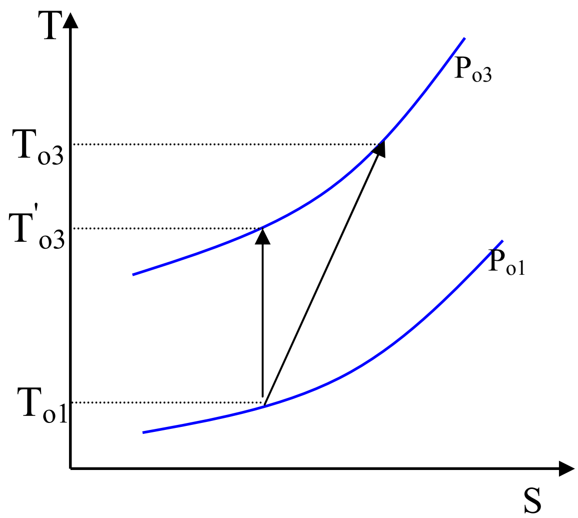
<u>Pressure ratio:</u>
1-Stage Pressure Ratio

$$\zeta_s = \frac{T'_{o3} - T_{o1}}{T_{o3} - T_{o1}}$$

$$\left(\frac{P_{o3}}{P_{o1}}\right) = \left(\frac{T'_{o3}}{T_{o1}}\right)^{k/k-1}$$

$$\left(\frac{P_{o3}}{P_{o1}}\right) = \left(1 + \frac{(T_{o3} - T_{o1})\zeta_s}{T_{o1}}\right)^{k/k-1}$$

$$Rs = \left(1 + \frac{\Delta T_{os}\zeta_s}{T_{o1}}\right)^{k/k-1}$$



Overall Pressure Ratio

$$R_t = \left(1 + \frac{n\Delta T_{os}}{T_{o1}} \right)^{k\eta_\infty / k-1}$$

Degree of Reaction

It is defined as the ratio of the static enthalpy increas in the rotor to that in the whole stage. If one assume that the specific heat remains constant through the stage, this quantity (X) will be equal to the ratio of corresponding temperatures.

$$X = \frac{C_p(T_2 - T_1)}{C_p(T_3 - T_1)}$$

$W = C_p \, \Delta Tos = C_p \, \Delta Ts$
$C_p \, \Delta Ts = U \, Ca \, (\tan \alpha_2 - \tan \alpha_1)$

Since all the input work is transferred to the air by the mean of rotor ; then the energy equation is

$$W = Cp(T_2 - T_1) + \frac{1}{2}\left(C_2^2 - C_1^2\right)$$

$$Cp(T_2 - T_1) = U \, Ca(\tan\alpha_2 - \tan\alpha_1) - \frac{1}{2}\left(C_2^2 - C_1^2\right)$$

$C1 = Ca \sec \alpha_1$, $C_2 = Ca \sec \alpha_2$

$$X = \frac{U \, Ca\left(\tan\alpha_2 - \tan\alpha_1\right) - \frac{1}{2} C_a^2 \left(\sec^2\alpha_2 - \sec^2\alpha_1\right)}{U \, Ca\left(\tan\alpha_2 - \tan\alpha_1\right)}$$

$$X = \frac{U \, Ca\left(\tan\alpha_2 - \tan\alpha_1\right) - \frac{1}{2} C_a^2 \left(\tan^2\alpha_2 - \tan^2\alpha_1\right)}{U \, Ca\left(\tan\alpha_2 - \tan\alpha_1\right)}$$

$$\boxed{\therefore X = 1 - \frac{Ca}{2U}\left(\tan\alpha_2 + \tan\alpha_1\right)}$$

Referring to equ. 1 and 2

$$\frac{2U}{Ca} = \left(\tan\alpha_1 + \tan\beta_1 + \tan\alpha_2 + \tan\beta_2\right)$$

$$\boxed{\therefore X = \frac{Ca}{2U}\left(\tan\beta_1 + \tan\beta_2\right)}$$

General Notes:

1- When X=0.5 (50%), This result in: $\beta_2 = \alpha_1$ and $\beta_1 = \alpha_2$, This case is termed as *Symmetric design.*

2- For free vortex design: $C_w\, r$ =constant.

Example: A single stage axial flow compressor with isentropic efficiency of 80%. The comperessor delivers 20 kg/s of air at a rotational speed of 9000 rpm, the stagnation temperature rise is 20 K and the axial velocity is 150 m/s, the mean blade speed is 180 m/s and λ=0.94. The degree of reaction is 50% at mean radius. Take the ambient conditions as 1 bar and 288 K. Find

1) Blade and air angles (α_1, α_2, β_1, and β_2)
2) Stage pressure ratio
3) Blade height