Ene-47.121

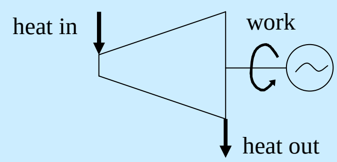
Turbine technology

General

- Most of the issues and equations presented in these slides are valid for both steam and gas turbines.
- With some topics steam and gas turbines are handled separately.

Turbomachines

- Turbines are turbomachines that transfer energy from continuous stream of fluid into the rotating turbine shaft
- Conversion of thermal energy to mechanical energy

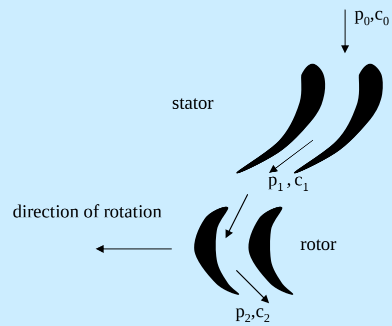


Gategorization of turbines

- By working media
  - Steam
  - Combustion gas
- By flow direction
  - axial flow
  - radial flow (Ljungström)
- By working method
  - impulse turbines
  - reaction turbines

Turbine stage

- A turbine stage consists of stationary stator row (guide vanes, nozzle ring etc.) and rotating rotor row.
- In the guide vanes high pressure, high temperature gas/steam is expanded and its speed is increased.
- The guide vanes also direct the flow to the rotor blades at an appropriate angle.



Turbine stage

- In the rotor the flow direction is changed and kinetic energy of the working fluid is passed on to the rotor shaft.
- Typically a turbine has 1 to 20 stages depending mainly on the pressure difference over the turbine.

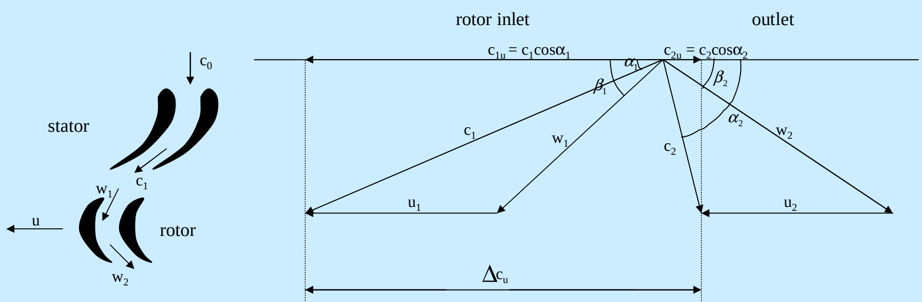
Velocity triangles

- Velocity triangles are used to illustrate the flow in the turbine blading
- Changes in the flow direction and velocity are easy to understand with the help of the velocity triangles
- Note that the velocity triangles are drawn for the rotor inlet and outlet at a certain radius (usually mean diameter)

Velocity triangles

- The subindexes in the equations and triangles: 0 = before the guide vanes
  1 = after the guide vanes
  2 = after the rotor
- In these slides the left triangle is for the rotor inlet and the right for rotor outlet
- The angles are measured from the plane of rotation

Velocity triangles



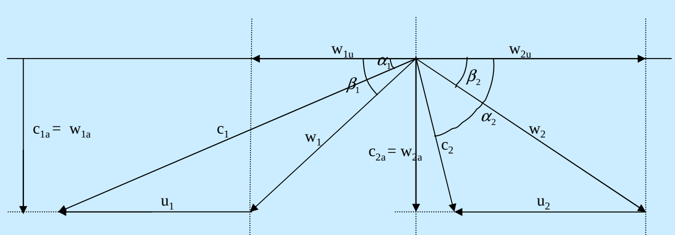
The velocity triangles can be described with vector equations:

$$\overline{c_1} = \overline{w_1} + \overline{u_1}$$

$$\overline{c_2} = \overline{w_2} + \overline{u_2}$$

c = absolute velocity
w = relative velocity
u = peripheral velocity
c_u = peripheral component of absolute velocity
α = angle made by absolute velocity
β = angle made by relative velocity

Velocity triangles



Trigonometry gives:

$$w_{1u} = w_1 \cdot \cos\beta_1$$

$$w_{2u} = w_2 \cdot \cos\beta_2$$

Peripheral components of relative velocities.

$$c_{1a} = c_1 \cdot \sin\alpha_1$$

$$c_{2a} = c_2 \cdot \sin\alpha_2$$

Axial components of absolute velocities.

$$w_{1a} = w_1 \cdot \sin\beta_1$$

$$w_{2a} = w_2 \cdot \sin\beta_2$$

Axial components of relative velocities.

$$c_{1a} = w_{1a}$$

$$c_{2a} = w_{2a}$$

The Euler turbomachinery equation

Tangential force acting on the rotor:

$$F_u = m(c_{1u} - c_{2u})$$

Torgue (change in the moment of momentum):

$$M = F_u \cdot r = m(r_1 \cdot c_{1u} - r_2 \cdot c_{2u})$$

Power on the shaft:

$$P = M \cdot \omega = m(\omega \cdot r_1 \cdot c_{1u} - \omega \cdot r_2 \cdot c_{2u})$$
$$P = m(u_1 \cdot c_{1u} - u_2 \cdot c_{2u})$$

The Euler turbomachinery equation

Power output per unit mass:

$$a_u = \frac{P}{m} = u_1 \cdot c_{1u} - u_2 \cdot c_{2u}$$

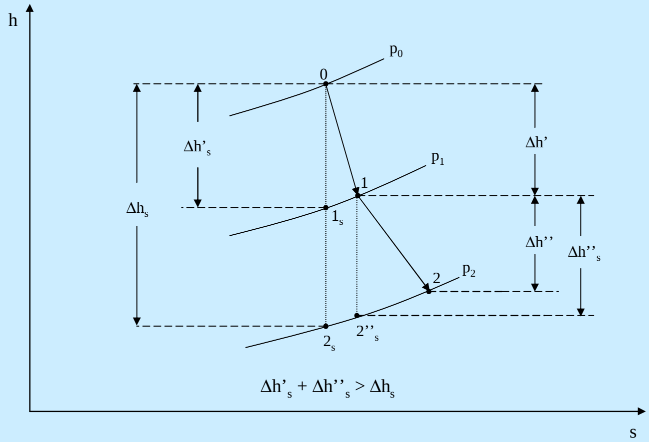
which is called the Euler turbomachinery equation (Leonard Euler, 1707-1783)

In an axial flow turbine $u_1 = u_2$ and equation can be written:

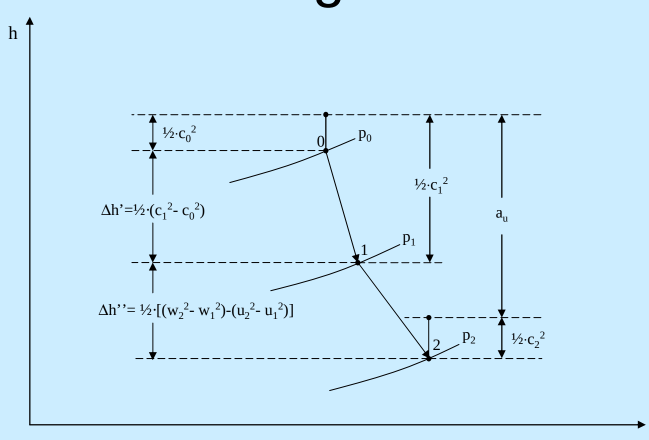
$$a_u = u \cdot \Delta c_u$$

The Euler turbomachinery equation is applicable also to blowers, pumps and compressors.

Turbine stage in h,s - diagram



Turbine stage in h,s - diagram



Turbine stage in h,s - diagram

Stator: $\Delta h' = h_0 - h_1 = ½\cdot(c_1^2 - c_0^2)$

Rotor:

fixed coordinates: $\Delta h'' = h_1 - h_2 = a_u - ½\cdot(c_1^2 - c_2^2)$

rotating coordinates: $\Delta h'' = h_1 - h_2 = ½\cdot[(w_2^2 - w_1^2) - (u_2^2 - u_1^2)]$

$$\Rightarrow a_u = ½\cdot[(c_1^2 - c_2^2) + (w_2^2 - w_1^2) - (u_2^2 - u_1^2)]$$

a_u is the available specific work

Degree of reaction

The degree of reaction for a turbine stage is defined as:

$$R = \frac{\text{static enthalpy change in the rotor}}{\text{static enthalpy change in the stage}}$$

$$\Rightarrow R = \frac{\Delta h''}{\Delta h' + \Delta h''} = \frac{\Delta h''}{\Delta h}$$

By substituting enthalpies we get:

$$R = \frac{\left(w_2^2 - w_1^2\right) - \left(u_2^2 - u_1^2\right)}{\left(c_1^2 - c_0^2\right) + \left(w_2^2 - w_1^2\right) - \left(u_2^2 - u_1^2\right)}$$

Degree of reaction

Assumptions:

$c_0 = c_2$, absolute velocity is the same before and after the stage
$u_1 = u_2$, axial flow turbine - constant peripheral velocity
$c_{1a} = c_{2a}$, axial velocity component is constant

Degree of reaction becomes:

$$R = \frac{\left(w_2^2 - w_1^2\right)}{\left(c_1^2 - c_2^2\right) + \left(w_2^2 - w_1^2\right)}$$

Degree of reaction

<u>Impulse turbine</u>

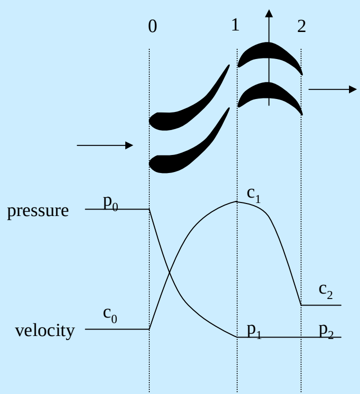
If $w_1 = w_2$ or $(w_2^2 - w_1^2) = (u_2^2 - u_1^2)$, R becomes zero. This special case is called an impulse stage.

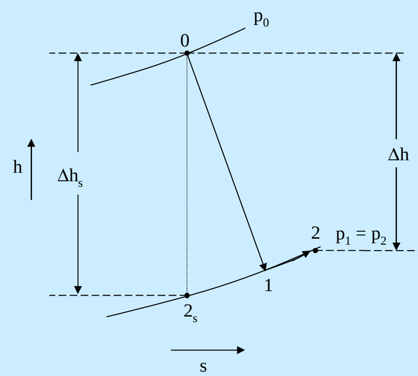
<u>Reaction turbine</u>

Any case when $R \neq 0$, is a reaction stage. A special case of a reaction turbine is R=0.5 ,which leads to symmetrical velocity triangles and is a very common design.

Impulse turbine

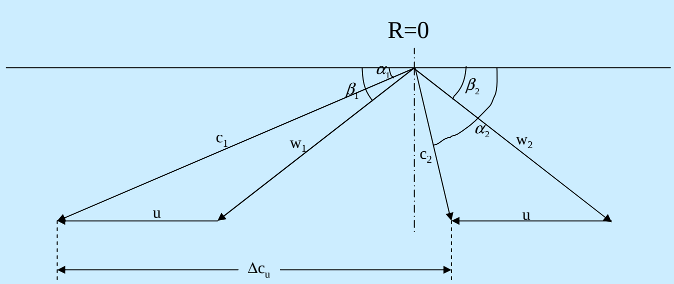
- Expansion takes place only in the guide vanes.
- No static pressure drop in the rotor.





Impulse turbine

<u>The velocity triangles of an impulse turbine stage</u>



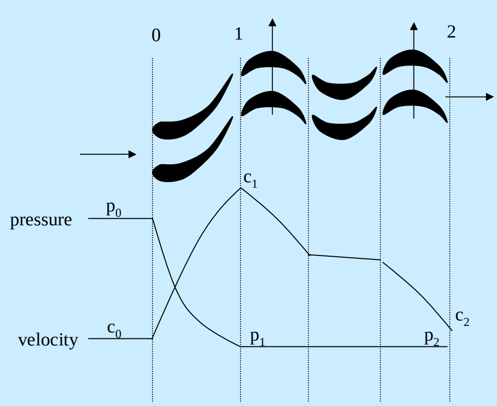
$\beta_1 = \beta_2$
$w_1 = w_2$

Impulse turbine

- Best efficiency when $u/c_1 = \cos\alpha_1/2 \approx 1/2$
- Optimum value of α_1 about 20°
- High peripheral velocity (rotation speed) needed when c_1 is high.
- Rotation speed can be lowered by dividing the velocity drop to two or more similar impulse stages (Curtis-turbine)

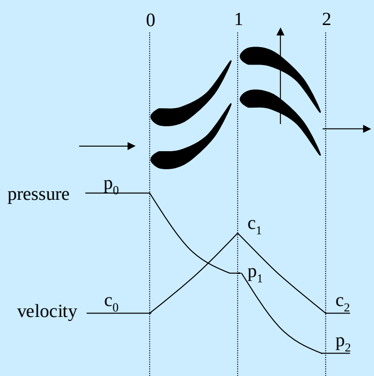
Impulse turbine

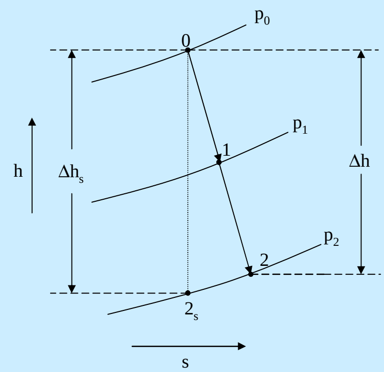
Curtis-turbine with two stages



Reaction turbine

- Expansion takes place in both stator and rotor

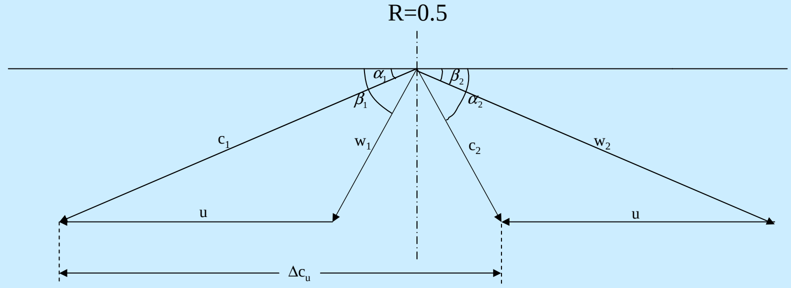




Reaction turbine

The velocity triangles of a reaction stage

R=0.5



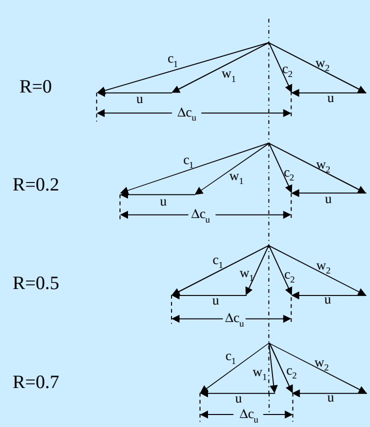
$c_1 = w_2$
$w_1 = c_2$
$\alpha_1 = \beta_2$
$\beta_1 = \alpha_2$

Reaction turbine

- Best efficiency for R=0.5 reaction stage is achieved when $u/c_1 = \cos\alpha_1 \approx 1$
- Optimum value of α_1 about 20°

Reaction turbine

- Δc_u decreases when R increases



Impulse - Reaction

- Δc_u is higher in impulse turbines, which means that an impulse stage does more work than a reaction stage with the same peripheral velocity
- Smaller number of impulse stages than reaction stages needed for a certain enthalpy drop

Impulse - Reaction

- More friction losses in an impulse turbine due to larger change in flow direction (angle between w_1 and w_2)
- Pressure difference over the rotor in a reaction turbine
  - an axial force to the direction of the flow
  - more leakage - special balancing valve is needed

Impulse - Reaction

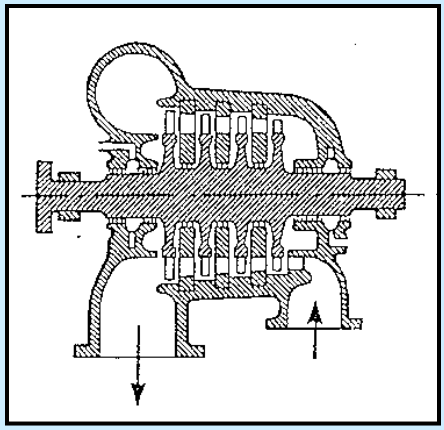
- Manufacturers nowadays try to combine the best features of both turbine types
- Usually the first stage is impulse-type (control stage) and the rest are reaction stages with R=0.5

Construction

- Axial flow turbines can be divided in two types, based on their rotor construction
  - disc turbines
    - the rotor consists of discs
    - the blades are on the rim of each disc
  - drum turbines
    - the blades are attached to the drum-shaped shaft

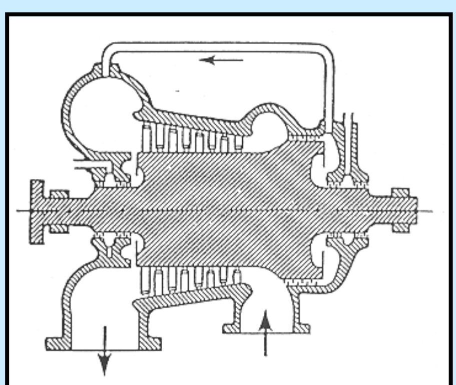
Construction

- Disc turbine
  - between the rotor discs are separating walls with guide vanes
  - requires large space in the axial direction due to the separating walls
  - mostly impulse turbines



Construction

- Drum turbine
  - shorter construction than disc turbine
  - larger shaft radius means more leakage between the guide vanes and the rotor than in disc turbine
  - mostly reaction turbines

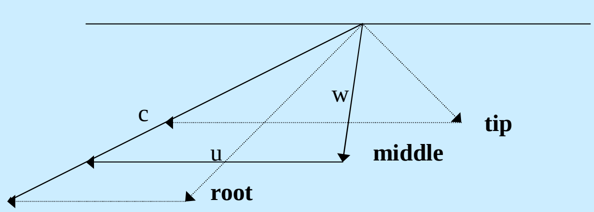


Twisted blades

- Energy transfer ($u\Delta c_u$ in Euler´s equation) to the rotor should be uniformly distributed along the blade lenght
- Due to centrifugal force the static pressure of the working fluid increases with increasing radius
- The pressure difference over the stator is therefore highest at the blade root and lowest at the blade tip

Twisted blades

- As a result of the uneven pressure distribution, the absolute velocity and the mass flow per area vary with radius



Twisted blades

- Fluid with density ρ and peripheral velocity component c_u passes through an circular area of A=2πrdr.
- The mass per unit widht: $dm = \rho \cdot 2 \cdot \pi \cdot r \cdot dr$
- Centripetal force acting on the mass:

$$F_c = a \cdot dm = \rho \cdot 2\pi \cdot r \cdot dm \cdot \frac{c_u^2}{2}$$

Twisted blades

- Between radii r and r+dr, the centripetal force makes a pressure difference:

$$2\pi \cdot r \cdot dp = \rho \cdot 2\pi \cdot r \cdot dr \cdot \frac{c_u^2}{r}$$

$$\Rightarrow \frac{1}{\rho} \cdot \frac{dp}{dr} = \frac{c_u^{\ 2}}{r}$$

- This is the static pressure - centripetal force balance requirement

Twisted blades

- Total enthalpy of the working fluid after the guide vanes: $h^* = h + \frac{1}{2} \cdot c^2$
- Differentiated with respect to r:

$$\frac{dh^*}{dr} = \frac{dh}{dr} + c \cdot \frac{dc}{dr}$$

- The 2nd law of thermodynamics:

$$dh = T \cdot ds + \nu \cdot dp$$

Twisted blades

- Differentiating and substituting specific volume ν with density ρ:

$$\frac{dh}{dr} = T \cdot \frac{ds}{dr} + \frac{1}{\rho} \cdot \frac{dp}{dr}$$

- Eliminating static enthalpy:

$$\frac{dh^*}{dr} - T \cdot ds = c \cdot \frac{dc}{r} + \frac{1}{\rho} \cdot \frac{dp}{dr}$$

Twisted blades

- Substituting: $c^2 = c_u^2 + c_a^2 + c_r^2$

$$\Rightarrow \boxed{\frac{dh^*}{dr} - T \cdot ds = c_u \cdot \frac{dc_u}{dr} + c_a \cdot \frac{dc_a}{dr} + c_r \cdot \frac{dc_r}{dr} + \frac{1}{\rho} \cdot \frac{dp}{dr}}$$

Twisted blades

- Assuming that:
  - total enthalpy stays constant: $dh^* = 0$
  - isentropic flow: $ds = 0$
  - radial velocity component is zero: $c_r = 0$

$$\Rightarrow \boxed{c_u \cdot \frac{dc_u}{dr} + c_a \cdot \frac{dc_a}{dr} + \frac{1}{\rho} \cdot \frac{dp}{dr} = 0}$$

Twisted blades

- Substituting $\frac{1}{\rho} \cdot \frac{dp}{dr} = \frac{c_u^2}{r}$

$$\Rightarrow \boxed{c_a \cdot \frac{dc_a}{dr} + \frac{c_u}{r} \cdot \frac{d(r \cdot c_u)}{dr} = 0}$$

- This the radial equilibrium equation, which has two radius dependent variables.
- Setting c_a = constant, we get:

$$c_u \cdot \frac{d(r \cdot c_u)}{dr} = 0 \quad \Rightarrow \quad r \cdot c_u = K = \text{constant}$$

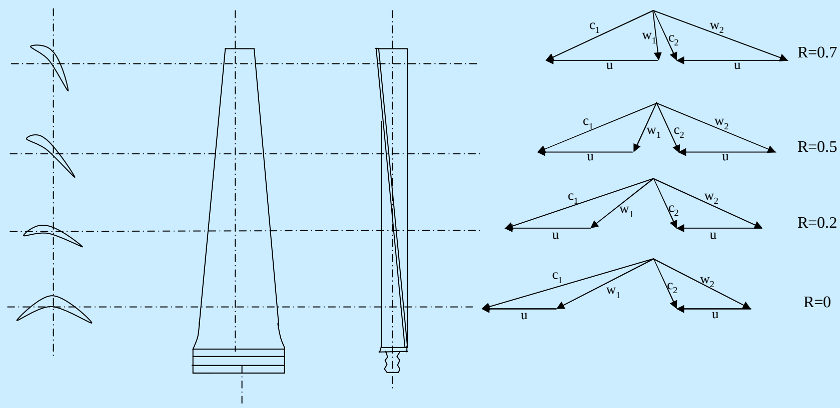
Twisted blades

- From the velocity triangles, we can obtain a simple relationship between the degree of reaction and the radius:

$$\boxed{\frac{1-R}{1-R_0} = \left(\frac{r_0}{r}\right)^2}$$

Twisted blades

- The angles made by velocities and the degree of reaction change with radius



Turbine´s losses

- Leakage
  - gap between the rotor blades and the casing
  - gap between the guide vanes and the rotor shaft
  - labyrinth sealings are used to minimize leakage
- Gap losses
  - part of the working fluid goes ”around” the blading

Turbine´s losses

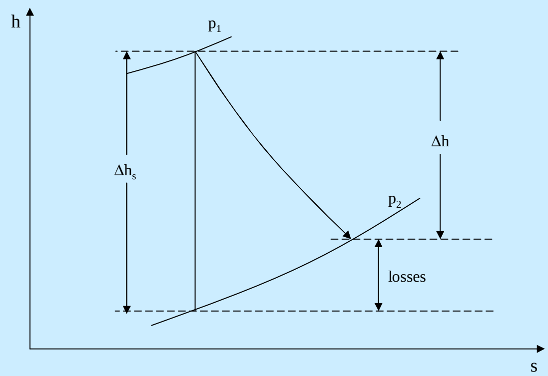
- In both stator and rotor blading
  - friction due to turbulence and whirl
- outflow loss
  - the kinetic energy of the outflow is not utilized
  - $h_{out} = ½c_2^2$
- disc friction
  - working fluid´s ”braking” effect on the rotor

Turbine´s losses

- Ventilation
  - in partial admission control stages
  - rotor segments that have no load cause braking effect
- Friction in bearings, etc.

Turbine´s losses

- Entropy is generated due to losses
- Isentropic efficiency: $\eta_s = \Delta h / \Delta h_s$



Turbine´s throughput

$$m = K \cdot \sqrt{\frac{p_1^2 - p_2^2}{p_1 \cdot v_1}}$$

K=constant
p_1=pressure before the section
p_2 =pressure after the section
ν_1 =specific volume

This ”cone rule” links the mass flow through the turbine to the working pressures. The equation holds quite accurately for a single turbine section (high pressure section, control stage etc.) It can be seen that higher pressure difference causes bigger mass flow and vice versa.

Turbine´s throughput

Usually $p_1 >> p_2$ and we can write the turbine equation simply:

$$m = K \cdot \sqrt{\frac{p_1}{v_1}}$$

The ”turbine constant” K in the equations represents the turbine´s throughput. With the help of the K-value calculated at design point, it is possible to get information about the turbine´s operation at partial load.

Power control

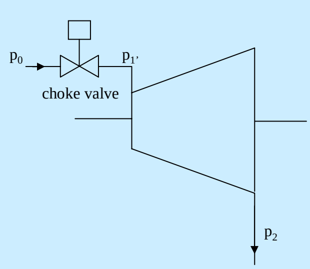
- Speed of rotation is held constant when the turbine is connected to a generator.
- The power of the turbine is determined by the load of the electrical network.
- Turbine´s output changes when the mass flow or the enthalpy drop in the blading changes.

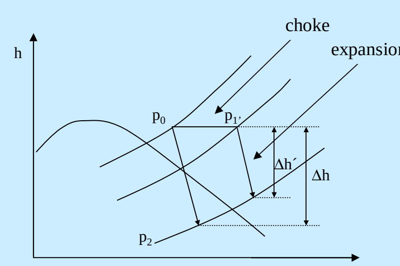
Steam turbine power control

- Throttle control
  - steam flow is choked before the turbine
  - pressure drops, but enthalpy stays constant
  - pressure difference over the turbine decreases, which leads to smaller mass flow
  - ”shorter” expansion
  - low efficiency at partial load

Steam turbine power control

Principle of throttle control



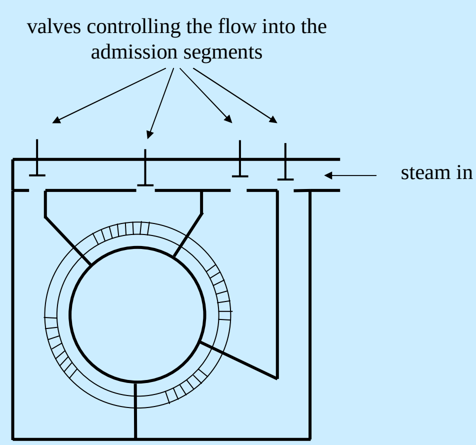


Steam turbine power control

- Throttling by a control stage
  - the control stage (of impulse type) is divided into segments, which all have their own choke valves
  - all valves are open at full power and they close one at a time when the load decreases
  - better efficiency at partial load compared to throttle control

Steam turbine power control

Throttling by a control stage

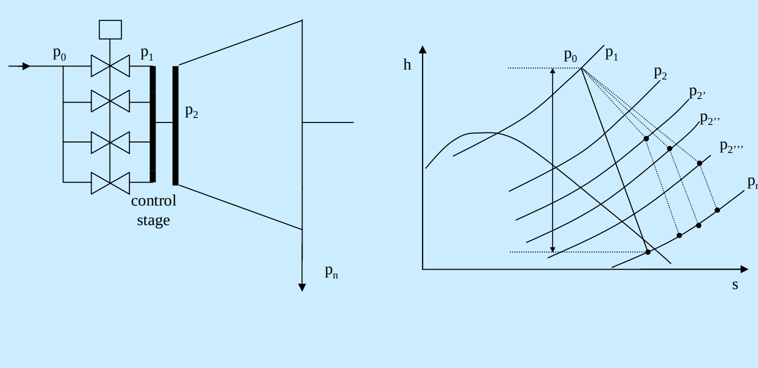


Steam turbine power control

- Throttling by a control stage
  - Not suitable for small volume flow rates, because the first stage blades would be too short (low efficiency)
  - The control stage must have low degree of reaction (near zero), otherwise the pressure difference over the rotor would cause uncontrolled flow and more losses

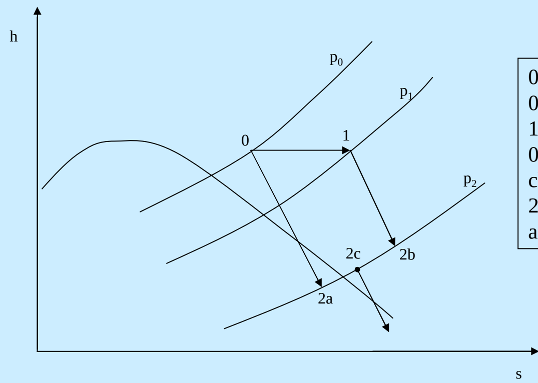
Steam turbine power control

Principle of throttling by a control stage



Steam turbine power control

Principle of throttling by a control stage



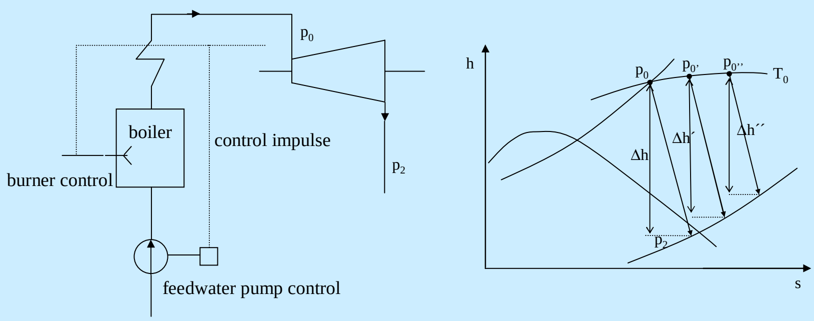
0: steam before the control stage
0-1: steam portion that is choked
1-2b: expansion of the choked steam
0-2a: expansion of the steam that is not choked (valve fully open)
2c: steam after the control stage (2a and 2b combined)

Steam turbine power control

- Sliding pressure
  - the boiler and the feedwater pumps co-operate in such a way that the steam has the desired pressure
  - usually steam temperature is held constant
  - rotation speed of the feedwater pumps is adjusted
  - advanced control method - requires advanced and expensive technology

Steam turbine power control

Principle of sliding pressure

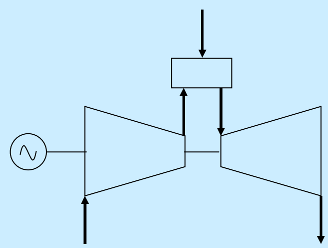


Characteristic for gas turbines

- Usually the pressure ratio is below 30 (up to 10000 in steam turbines)
- Turbine inlet temperatures much higher than in steam turbines, 1200°C vs. 600°C
  - strict requirements for the blade material
  - blade cooling needed
- High flue gas temperature after the turbine
  - enables topping process

Characteristic for gas turbines

- The pressure ratio in compressor stages much lower than in turbine stages (more stages in the compressor than in the turbine)
- No bleeds in the turbine



Characteristic for gas turbines

- Size range from 100kW to 300MW
- NOx emissions controlled
  - Low-NOx - burners
  - steam injection (STIG)

Gas turbine power control

- the blading of a gas turbine operates all the time with full mass flow (täyssyöstö)
- power output is controlled by adjusting the fuel mass flow into the combustion chamber
- flue gas temperature (enthalpy) changes
- adjustable guide vanes in the first compressor stages in order to enhance efficiency at part load