Introduction to Turbomachinery

Master Degree in Innovative Technologies in Energy Efficient Buildings for Russian & Armenian Universities and Stakeholders

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Power and energy

The power conversion system converts energy from a primary source to power in usable form

For instance chemical energy or power of a fuel

$\dot{m}_c H_i$ → Mechanical power → Electrical power

Fu Power for flight → Propulsion

$M\omega$ Mechanical power on a rotating shaft → Industrial machines

Energy = $\int P(t)dt \rightarrow \int_0^{8760} P(t)dt$

Power conversion systems

- An energy conversion system (or “energy system”) is an organized ensemble of different components connected each other that allows to transform a primary energy in an exploitable energy through the action of a working fluid (liquid, gas or vapor). These energy systems are often referred as “power plants”.

- The primary energy sources may be divided into two categories:
- Not renewable sources (coal, oil, natural gas, nuclear) because these types were accumulated in the past geological eras .
- Renewable sources (solar, hydraulic, wind, sea energy, biofuels, wastes) because these energy sources have a reconstruction rate comparable with the use velocity.

Power and energy

The majority of the energetic conversion is done using fluid machinery that are the main components of the energetic plant

Gas turbine plant
- Compressor
- Combustion chamber
- Turbine
- Propeller or fan/Electric generator

Hydraulic plant
- Dam
- Penstock
- Valves
- Turbine
- Exhaust duct
- Electric generator

Wind plant
- Wind: air flow with kinetic energy
- Wind turbine
- Electric generator
- Inverter

Fluid machinery

These machines, acting on a fluid that has thermal, pressure, potential and kinetic energy, receive work or mechanical power on a shaft or viceversa.

Fluid machines
- Those which absorb power to increase fluid pressure or head (compressor, pump)
- Those which produce power by expanding fluid to lower pressure or head (turbine)

Fluid machines
- Volumetric machines (for example internal combustion engines)
- Turbomachines

Turbomachinery

- The power exchange takes place in a continous manner while the fluid flows through the machine.

- The flow can be very fast and at high pressure.

- The specific energy is very large (Typically 10-15 kW/kg for an aero-engine).

- The shaft rotates at very high speed (large centrifugal forces to withstand).

Classification Criteria for Fluid-Machines

→ *Direction of energy transfer*

- *Motor machines convert the fluid energy in mechanical energy* (P, h ↓; $l < 0$)
- *Operating machines convert mechanical energy in fluid energy* (P, h ↑; $l > 0$)

→ *Thermal and volumetric behavior of the working fluid*

- *Incompressible flow machines, if the fluid does not exhibit its compressibility throughout the transformation (also called hydraulic machines)*
- *Compressible flow machines, if the fluid compressibility (i.e., thermal effects) are relevant for the transformation (also called thermal machines)*

→ *Operating way*

- *volumetric machines exchange energy by a cyclic change of volume (or displacement) of the fluid; low flow velocity (small flow rate), high work exchange*
- *turbomachines exchange energy by the continuous interaction between the fluid and the rotating components of the machine; high flow velocity (high flow rate), low energy exchange*

Relevant example: aero-engine vs ICE → turbomachinery vs pistons

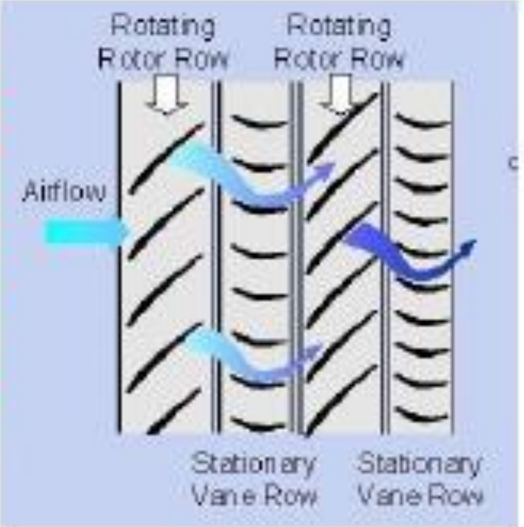
Turbomachinery

Working principle: aerodynamic forces exchanged between flow and moving blades

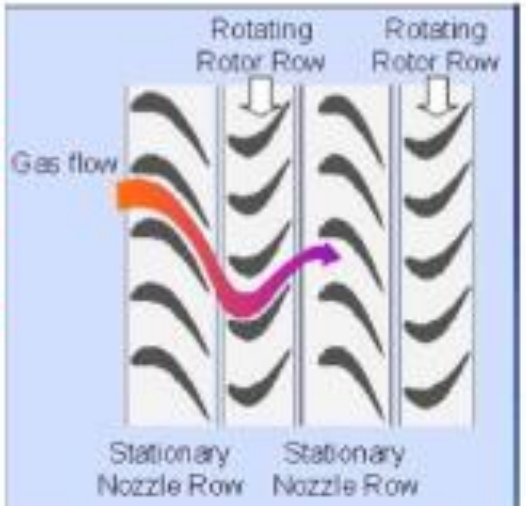
→ exchange of mechanical power: cross and transversal velocity components involved

→ blades inclined and cambered, both moving (rotor) and fixed (stator) blade rows

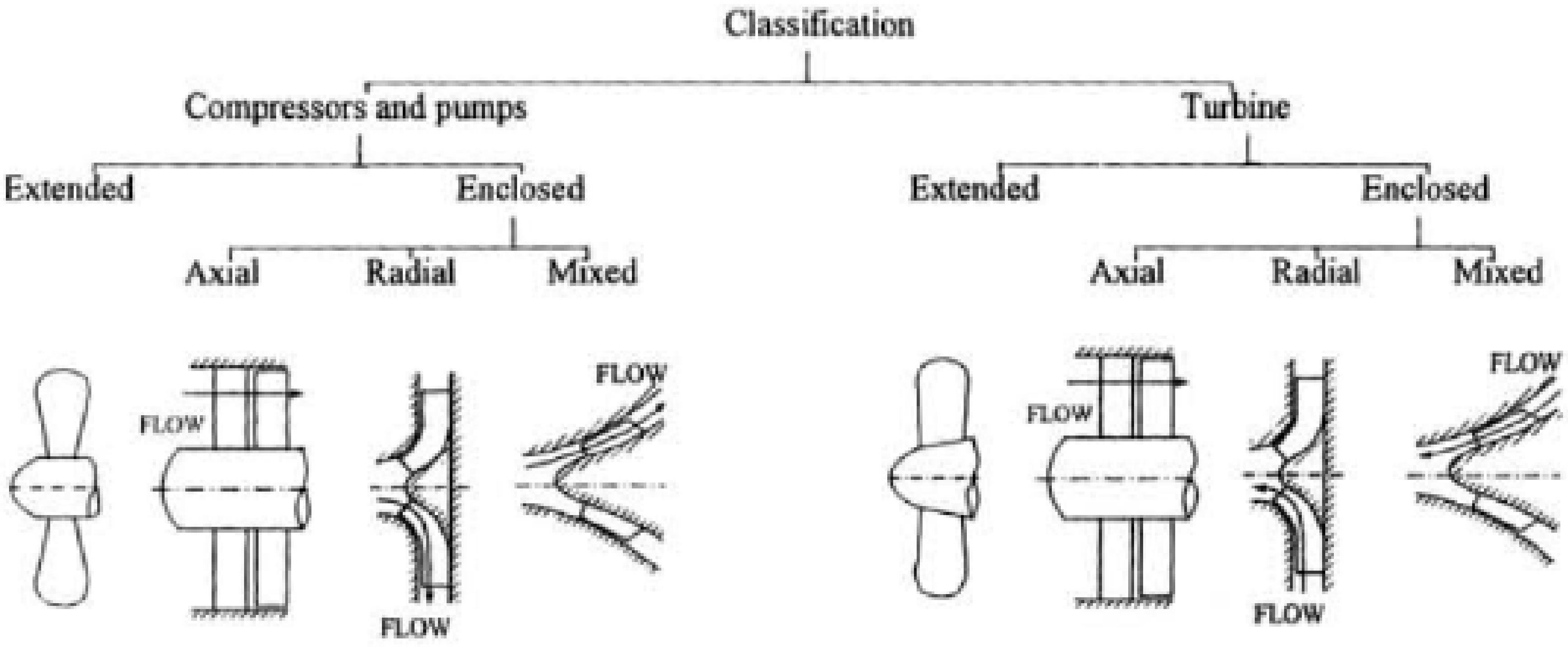
COMPRESSORS



TUBRINES



Meridional Architecture



Scheme taken from

Lakshminarayana, “Fluid Dynamics and Heat Transfer of Turbomachinery”)

Turbomachinery Classification

→ *Radial machines:*

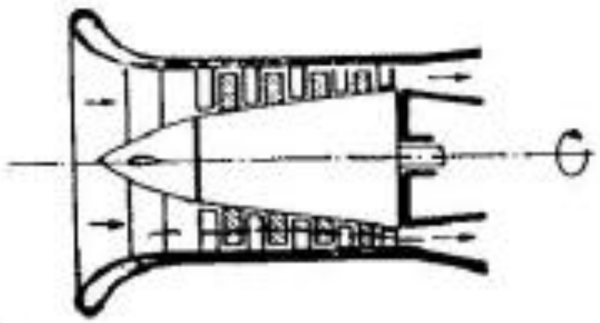
- *the flow passes throughout the machine mainly in radial direction*
- *the flow trajectories lie on conical surfaces and NOT cylindrical*
- *between inlet and outlet the flow changes significantly the distance from the axis, resulting in centripetal or centrifugal flow paths*
- *intrinsically suitable for low flow rates, relatively high specific work exchange*

→ *Axial machines:*

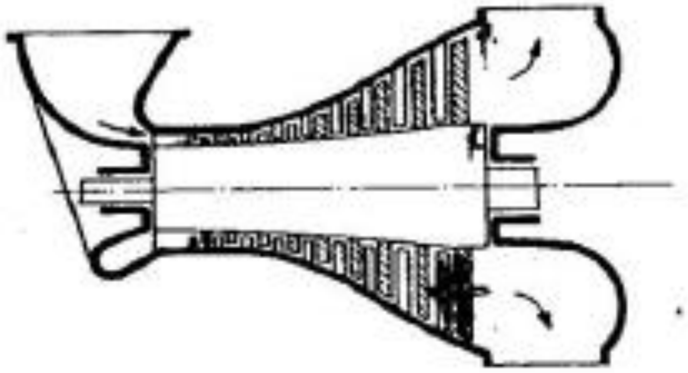
- *the flow passes throughout the machine mainly in axial direction*
- *the flow trajectories lie mainly on cylindrical surfaces*
- *between inlet and outlet the distance between the flow surface and the axis of the machine remains constant or does not change significantly*
- *intrinsically suitable for high flow rates, low specific work exchange*

→ *Mixed-flow machines: intermediate configuration*

Examples of Axial Turbomachines
→ typically in multi-stage configuration



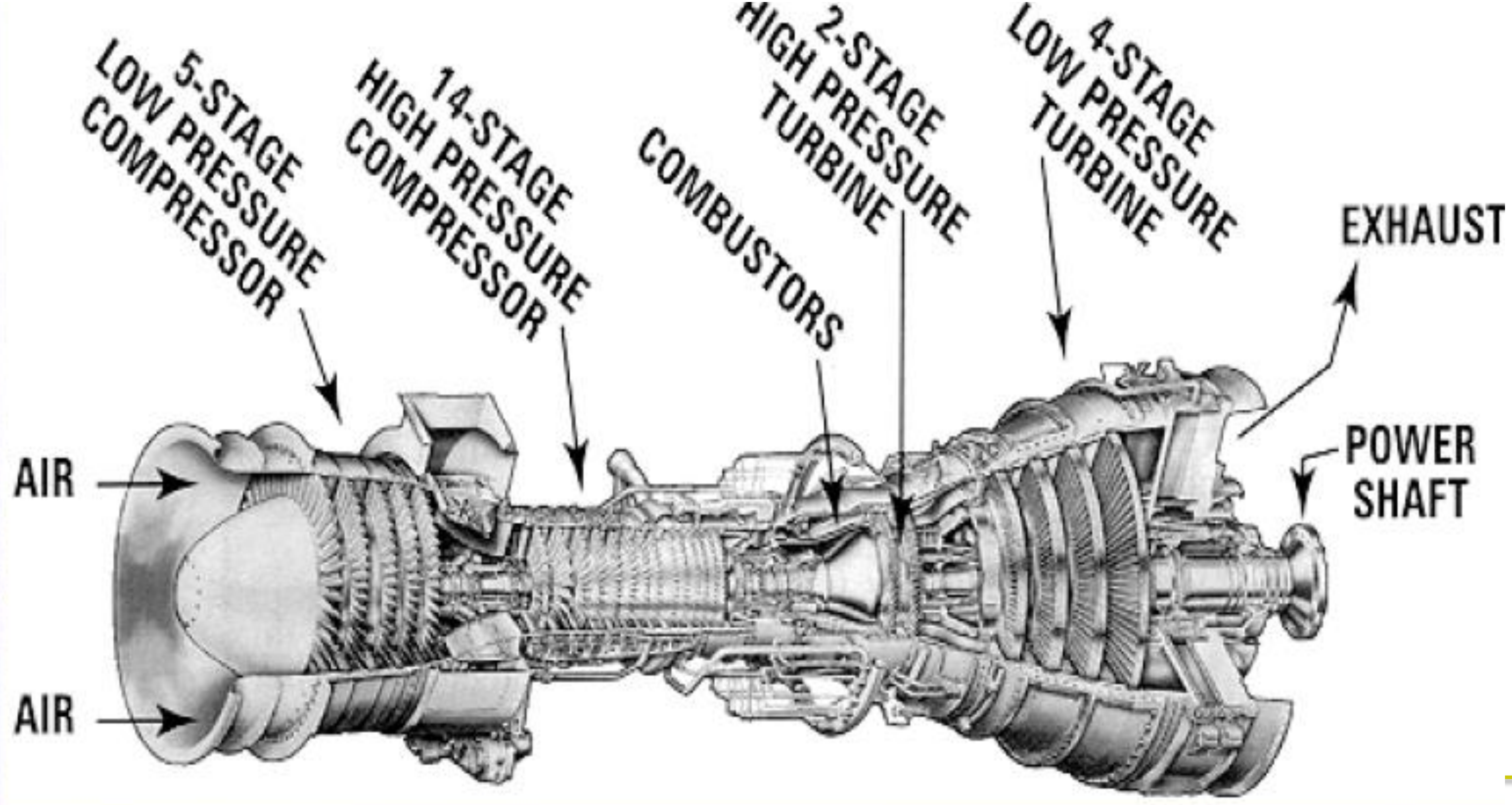
Axial compressor



Axial turbine

Gas Turbine plant (rotor assembly)

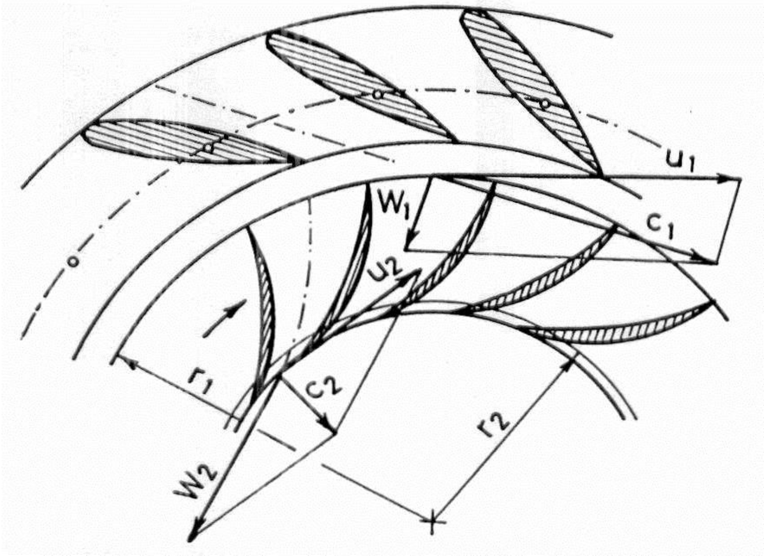
Aero-engine (power plant, propulsion system)



Centrifugal compressor

Francis turbine (2/2)

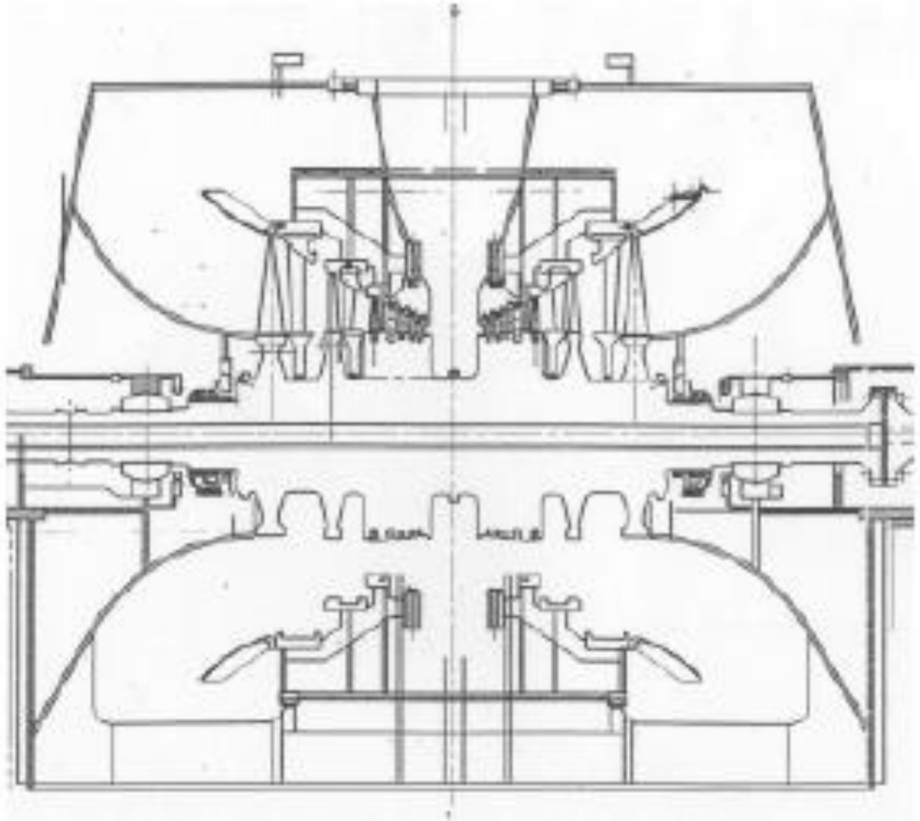
- Flowing through the distributor vanes, the water is accelerated transforming part of its pressure energy in kinetic energy and reaching a correct velocity directed tangentially to the rotor blades.
- The distributor blades can be rotated about fixed pivots by a servo-mechanism, so that the volume flow rate can be controlled. At any load, the distributor blades are turned at the best angle, so that the flow enters the runner without any impact.



Examples of Axial Turbomachines
→ even for dramatic change in cross-section

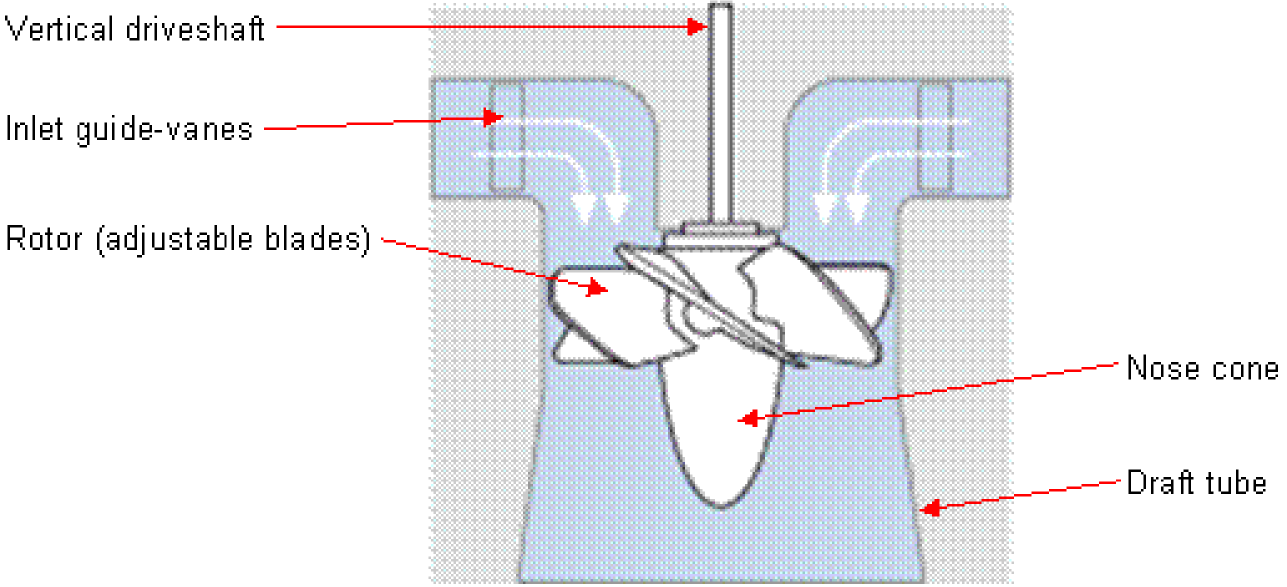
Low pressure axial steam turbine

(the dramatic change in mean diameter due to the increase of channel height does not affect the classification, which holds across each single rotor)



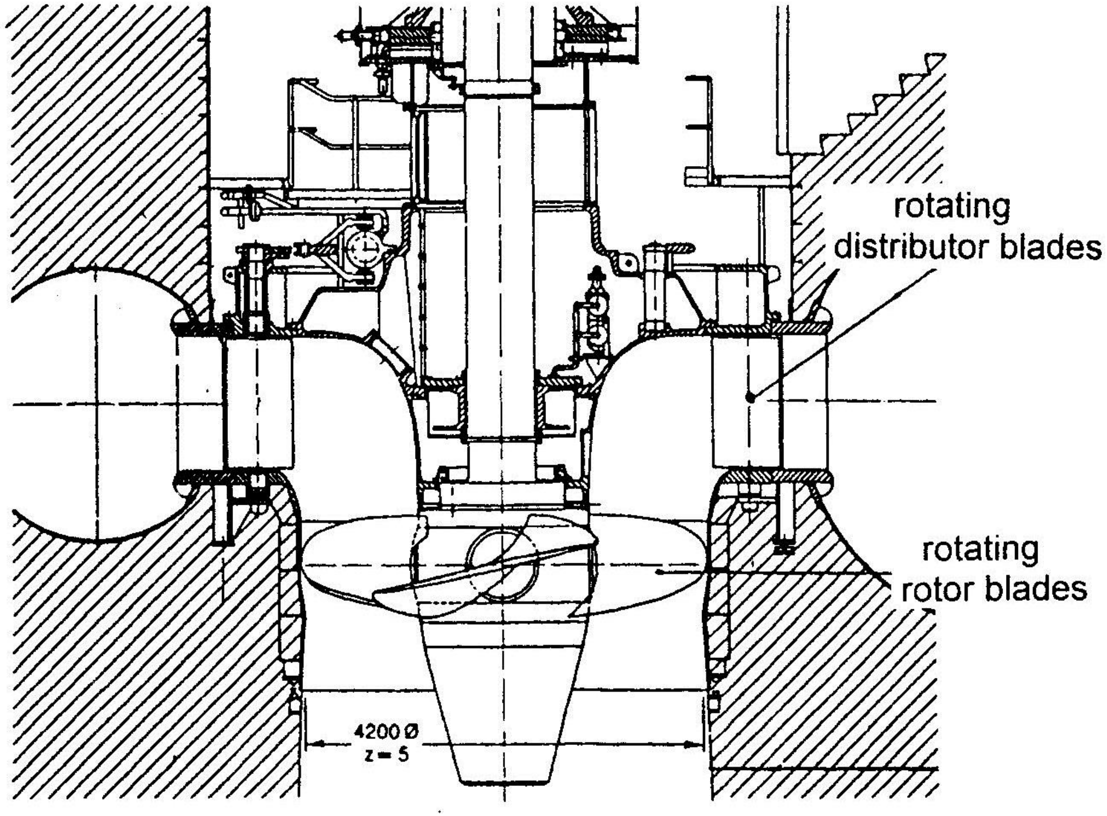
Kaplan turbine (1/2)

- Increasing the volume flow rate and decreasing the geodetic head, the shape of Francis turbine rotor changes: the radial development of the rotor blades decreases while their axial extent increases, in order to handle higher flow rates.
- For the highest water flow rates, Kaplan reaction turbines are used. In this case, not only the distributor blades are rotating , but also the rotor blades are adjustable and can be turned about pivots fixed to the runner, so that the triangles of fluid velocity are optimised at any turbine load.

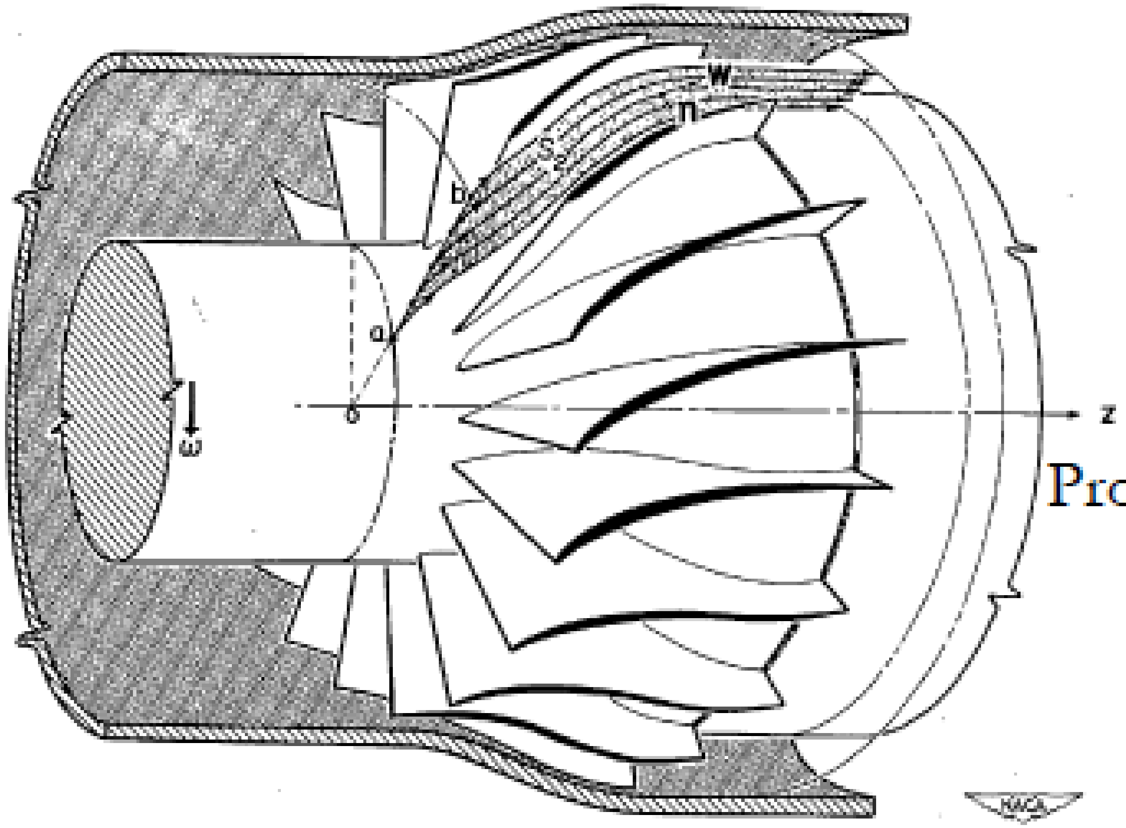


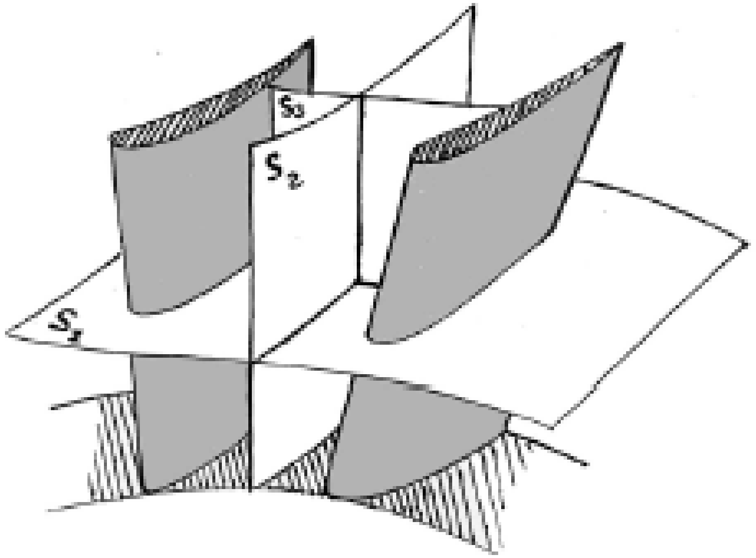
Kaplan turbine (2/2)

- Kaplan turbines are used for small geodetic heads (H' = 5-40 m) and very high water flow rates (up to 50 m^3/s). Power output ranges from 5 to 200 MW.

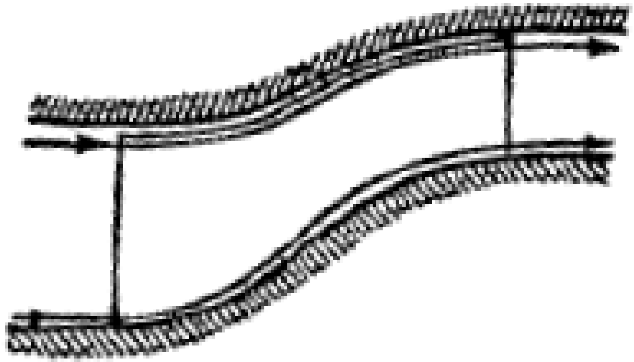


(a): Meridional surface, representing the channel between the endwalls

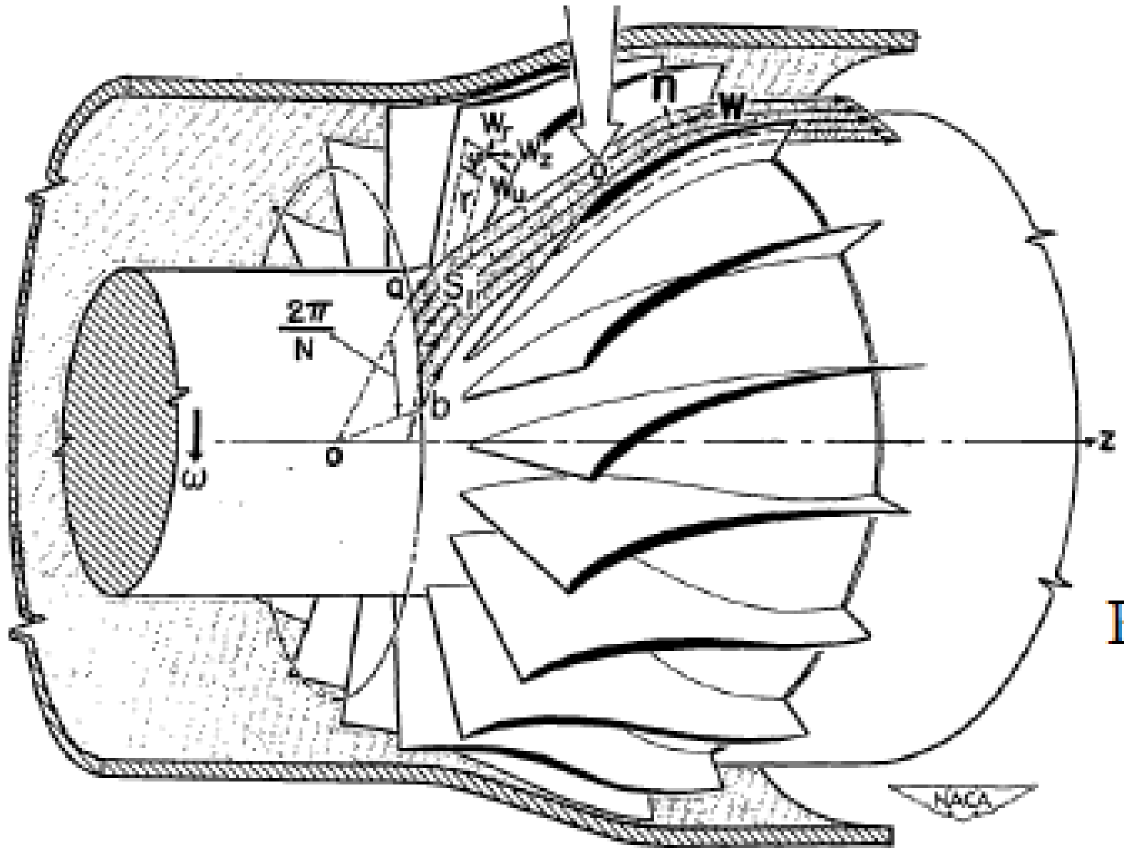


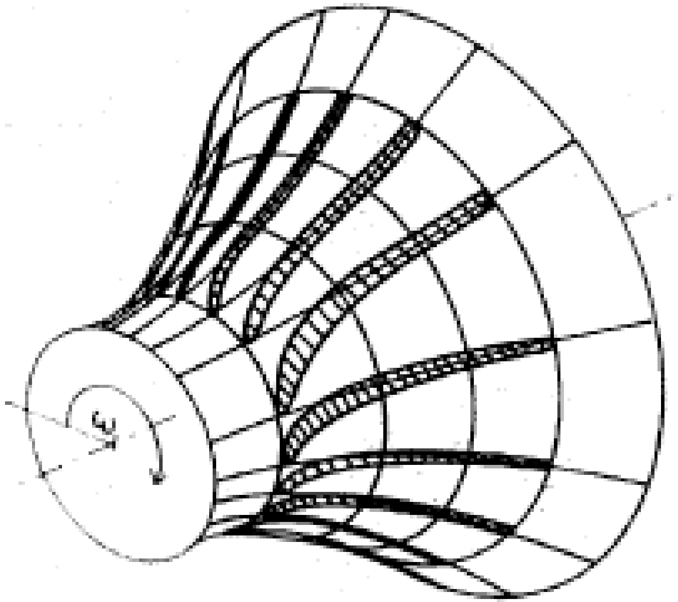


Projected on the meridional plane

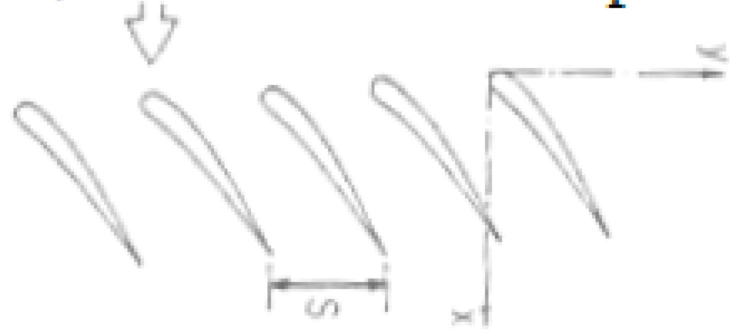


(b): Blade-to-blade surface, containing the blade profiles

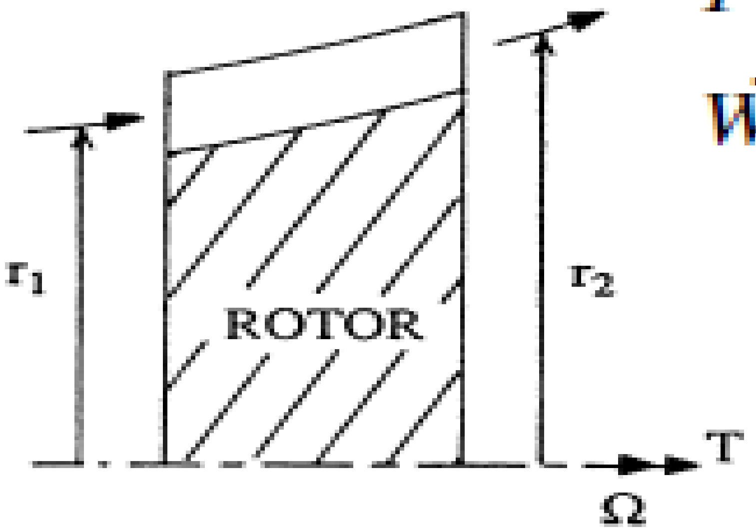




Projected on the bl-to-bl plane



THE EULER WORK EQUATION



$$T = \dot{m}(r_2 V_{\theta 2} - r_1 V_{\theta 1})$$

$$\dot{W} = T\Omega = \dot{m}\,\Omega(r_2 V_{\theta 2} - r_1 V_{\theta 1})$$

$$= \dot{m}(U_2 V_{\theta 2} - U_1 V_{\theta 1})$$

$$\Delta h_0 = U_2 V_{\theta 2} - U_1 V_{\theta 1}$$

A hypothetical rotor for which flow enters at radius r_1 and leaves at radius r_2. The torque created is T and the rotor rotates at Ω radian/s.

the torque is equal to the rate of change of moment of momentum

$$\Delta h_0 = U(V_{\theta 2} - V_{\theta 1}), \qquad \Delta h_0/U^2 = V_{\theta 2}/U - V_{\theta 1}/U$$

Euler expression for the work exchange

The power exchange results, with $U = \omega r$:

$$\dot{L} = \dot{m}\omega(r_{out}V_{t,out} - r_{in}V_{t,in}) = \dot{m}(U_{out}V_{t,out} - U_{in}V_{t,in})$$

Which, in specific terms, provides the Euler expression for the work exchange:

$$l = U_{out}V_{t,out} - U_{in}V_{t,in}$$

Considerations:

- no hypothesis are made on the nature of the transformation → the actual work and power are estimated provided that the actual flow velocity is used
- the peripheral speed of the rotor blade at inlet and outlet appears explicitly → justification for radial machines; high-speed peripheral speed induces high work
- the change (absolute) tangential velocity is crucial (especially for axial machines) → the blade profiles deflect the (relative) flow to induce the work exchange