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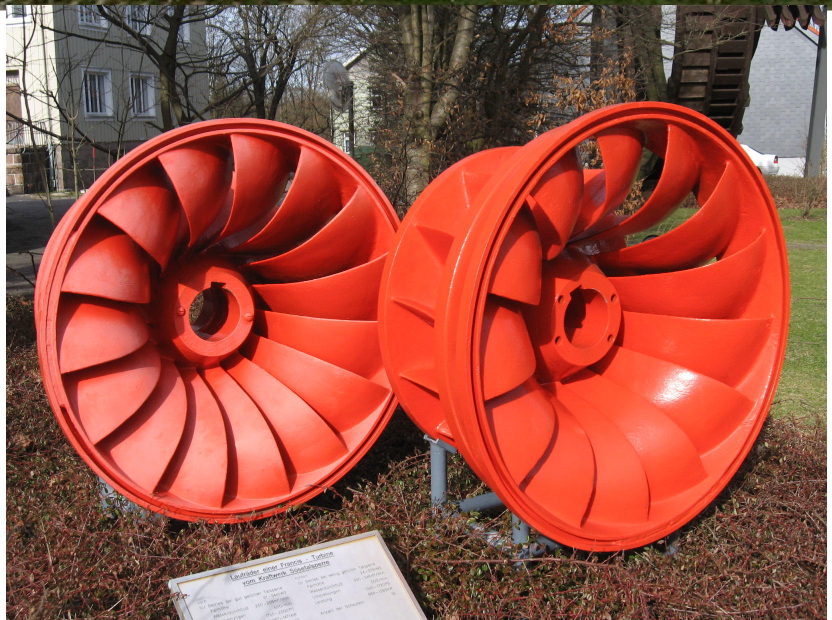

Chapter 10: Hydraulic Turbines 2

ME-342 Introduction to turbomachinery

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Recall- Turbines

Impulse or **reaction** : No matter the working fluid, turbines can be broadly classified into two types based on the mechanism of the fluid interaction

Impulse turbine: the force on the blades is produced solely by turning the fluid, without appreciable pressure drop in the blade passage, with all of the pressure drop occurring in a fixed nozzle.

Reaction turbine: some of the fluid-vane force is from fluid turning and some of the force is a reaction to acceleration of the fluid relative to the vane. In reaction blading, a pressure drop occurs in both a fixed nozzle and the moving vane.

Turbine blading is characterized by the **degree of reaction (R) (or simply reaction)**, which is the ratio of the drop in static pressure (or enthalpy) across the moving blade to the overall drop in static pressure (or enthalpy) across the fixed nozzle plus the moving blade. Impulse turbines have $R = 0$ while reaction turbines typically have $0.1 < R < 0.7$.

Recall- Degree of reaction or Reaction (R)

Change in static enthalpy across the **rotor** divided by the static enthalpy change across the entire **stage**

(static) Enthalpy: internal energy and flow work

$$\check{h} = \check{u} + \frac{p}{\rho} \quad \text{[J/kg]}$$

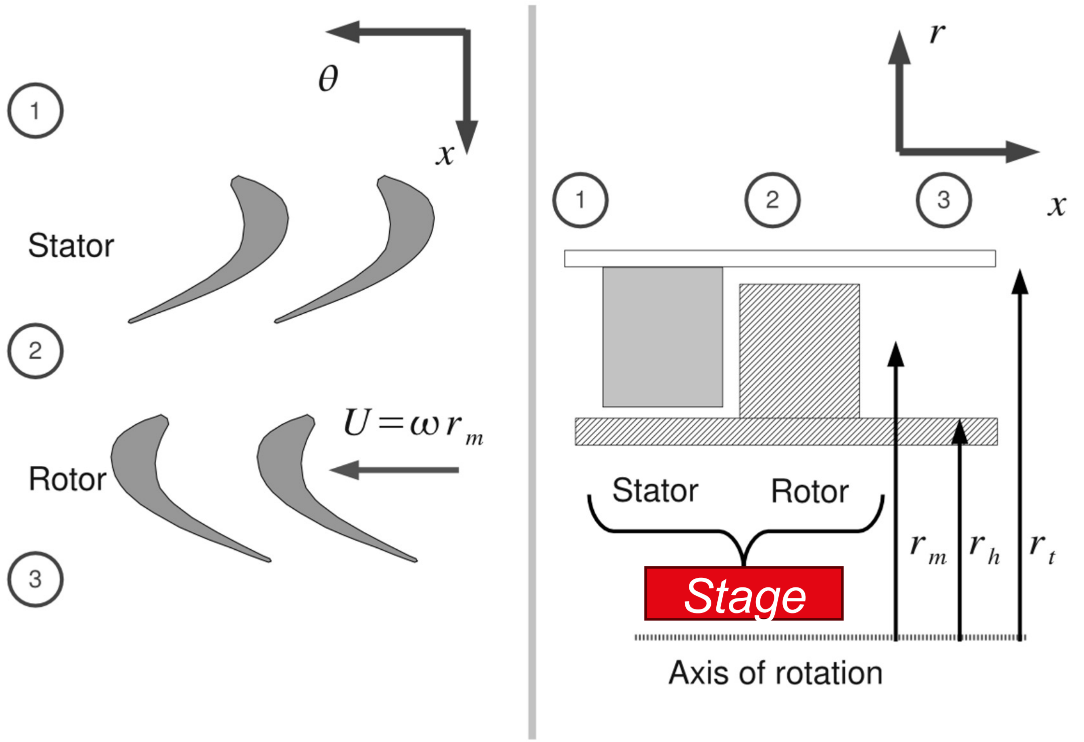
Internal energy

$\mathrm{Pa} \cdot \ \mathrm{m}^3/\mathrm{kg} \equiv \ \mathrm{J/kg}$

Stagnation enthalpy: sum of enthalpy, kinetic energy and potential energy

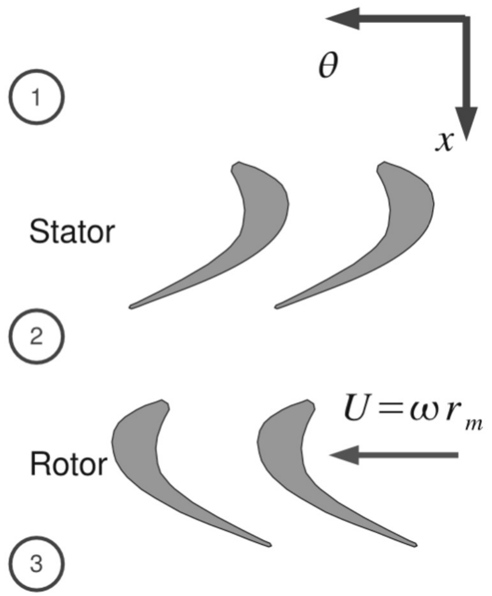
$$\check{h}_0 = \check{h} + \frac{V^2}{2} + gz$$

Achtung! $\check{h}$ is enthalpy, not head h or h_a



Recall- Degree of reaction or Reaction (R)

This concept is much used in axial flow machines as a measure of the relative proportions of energy transfer obtained by static and dynamic pressure change



(static) Enthalpy: internal energy and flow work

$$\check{h} = \check{u} + \frac{p}{\rho} \quad \text{[J/kg]}$$

$$R = \frac{\text{energy change due to, or resulting from, static pressure change in the **rotor**}}{\text{total energy change for a **stage**}}$$

$$R = \frac{\text{static enthalpy change in rotor}}{\text{static enthalpy change in stage}} = \frac{\check{h}_2 - \check{h}_3}{\check{h}_1 - \check{h}_3}$$

If no internal energy is changed, incompressible, $R \simeq \dfrac{p_2 - p_3}{p_1 - p_3}$

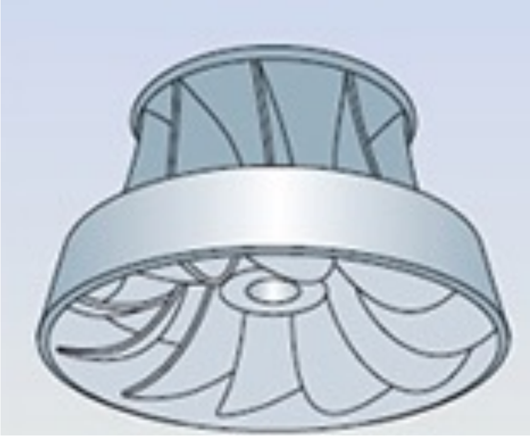
$$R = \frac{U_2^2 - U_3^2 + W_3^2 - W_2^2}{V_2^2 - V_1^2 + U_2^2 - U_3^2 + W_3^2 - W_2^2}$$

- If U_2=U_3 (axial machine), W_3=W_2 → R=0
- If V_1=V_2 → R=1

Recall-Types of hydraulic turbines

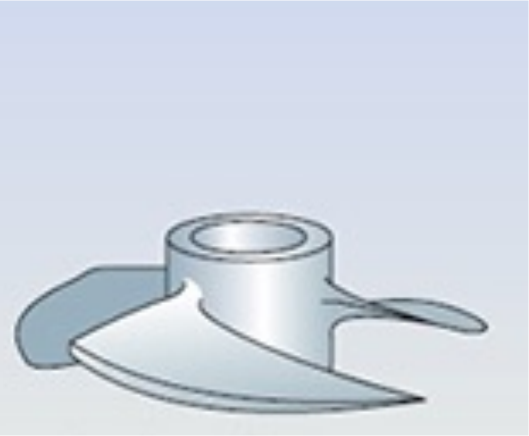
- Impulse (Action) turbines: Pelton turbines, R~0
- Reaction turbines: R~[0.1, 0.7]
  Francis turbines (radial et axial), Kaplan turbines (axial)
  Propeller turbines (similar to Kaplan turbines with fixed pitch)

Pelton



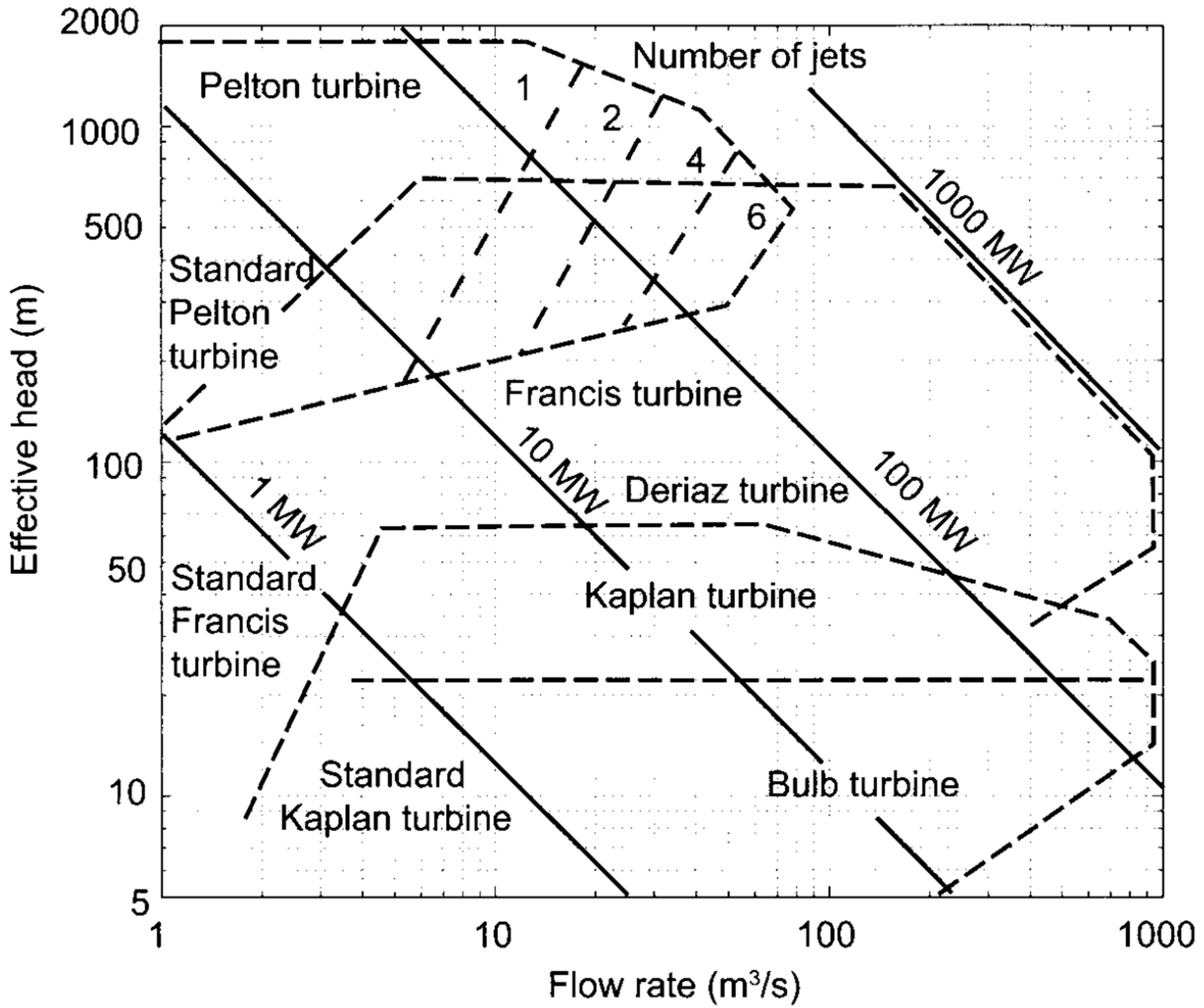
Francis

Kaplan & Bulb

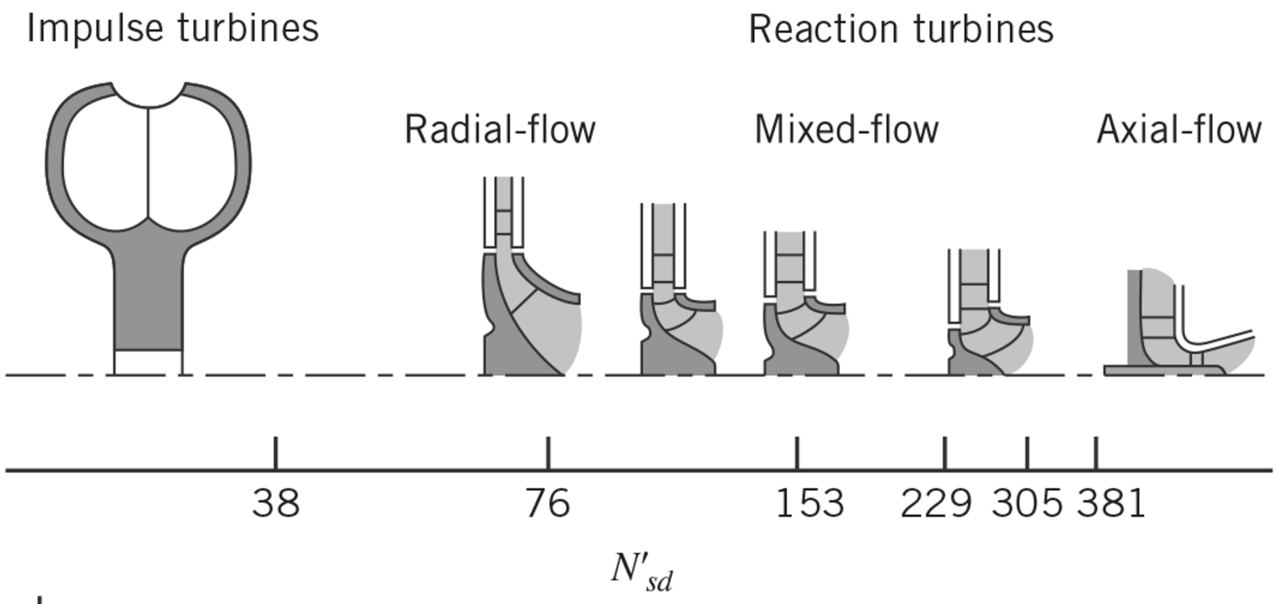


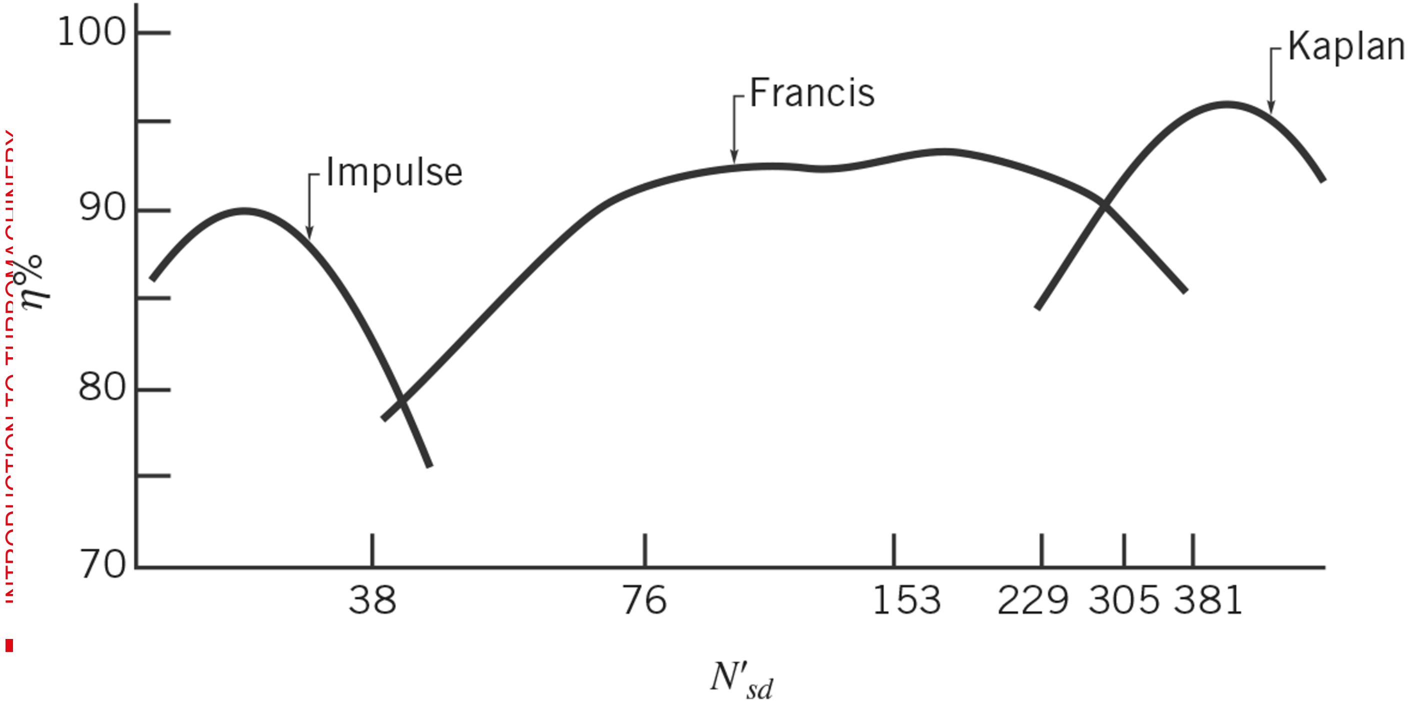
Fixed pitch propeller

Recall-Types of hydraulic turbines



Recall-Turbines





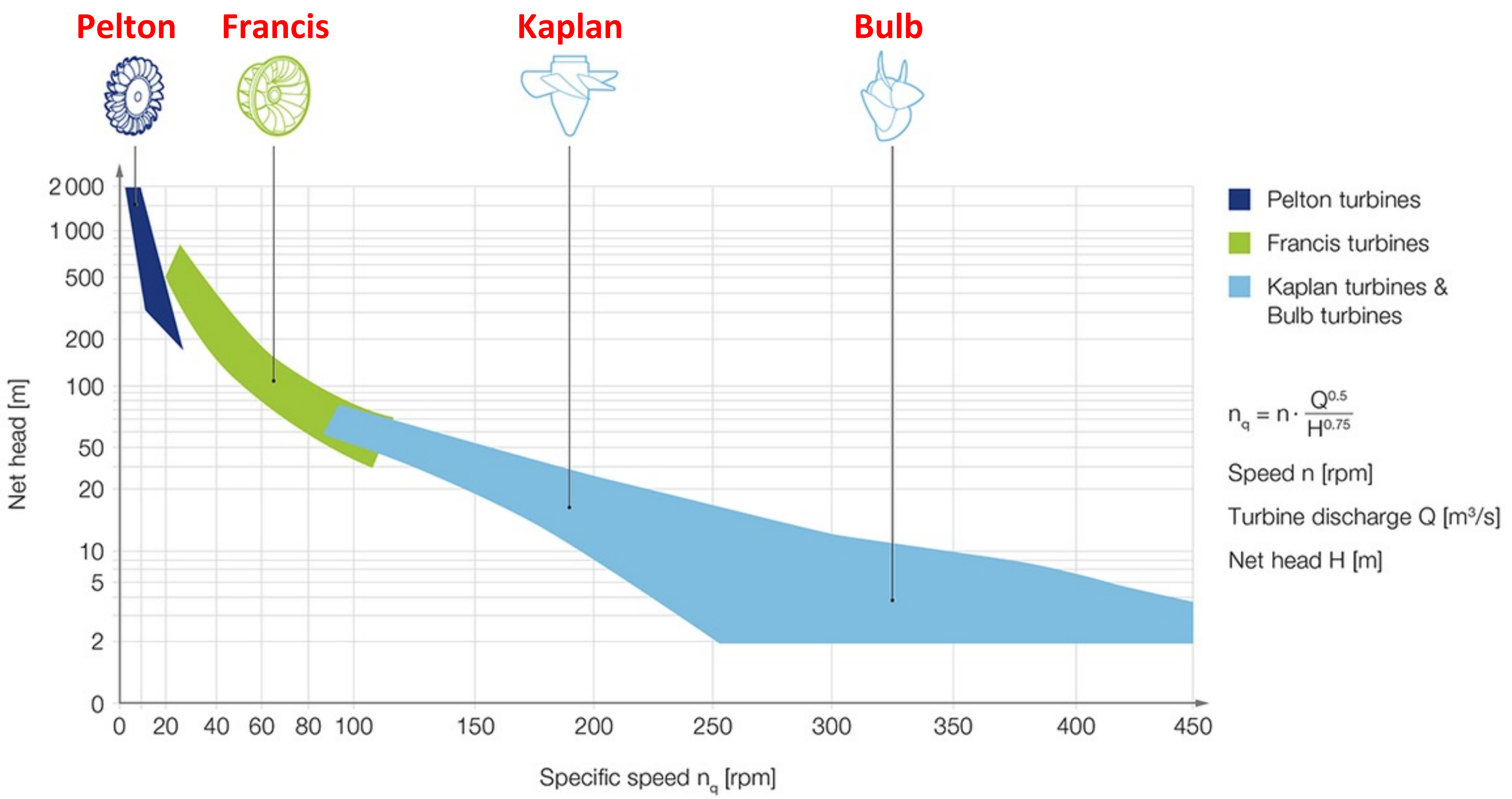
Power specific speed:

$$N_s' = \frac{\omega\sqrt{\dot{W}_{\text{shaft}}/\rho}}{(gh_a)^{5/4}}$$

Type		N_s'	η %
Pelton wheel			
	Single jet	0.02 – 0.18	88 – 90
	Twin jet	0.09 – 0.26	89 – 92
	Three jet	0.10 – 0.30	89 – 92
	Four jet	0.12 – 0.36	86
Francis			
	Low-speed	0.39 – 0.65	90 – 92
	Medium-speed	0.65 – 1.2	93
	High-speed	1.2 – 1.9	93 – 96
	Extreme-speed	1.9 – 2.3	89 – 91
Kaplan turbine		1.55 – 5.17	87 – 94
Bulb turbine		3 – 8	

Recall-Turbines

- Classification of turbine types as a function of the head and unit specific speed



Hydraulic Turbines – Reaction turbines

Reaction Turbines

The primary features :

(i) Only **part of the overall pressure drop** has occurred up to turbine entry; the **remaining pressure** drop takes place **in the turbine** itself

(ii) The flow **completely fills all of the passages in the runner**, unlike the Pelton turbine where, for each jet, only one or two of the buckets at a time are in contact with the water

(iii) Pivotable **guide vanes** are used to control and direct the flow

(iv) A **draft tube** is normally added to the turbine exit; this is considered an integral part of the turbine

As water flows through the runner, its pressure gradually decreases. This pressure drop is what gives the turbine its name: a reaction turbine.

The **angular momentum, pressure, and velocity of the fluid decrease** as it flows through the turbine rotor—the turbine rotor extracts energy from the fluid.

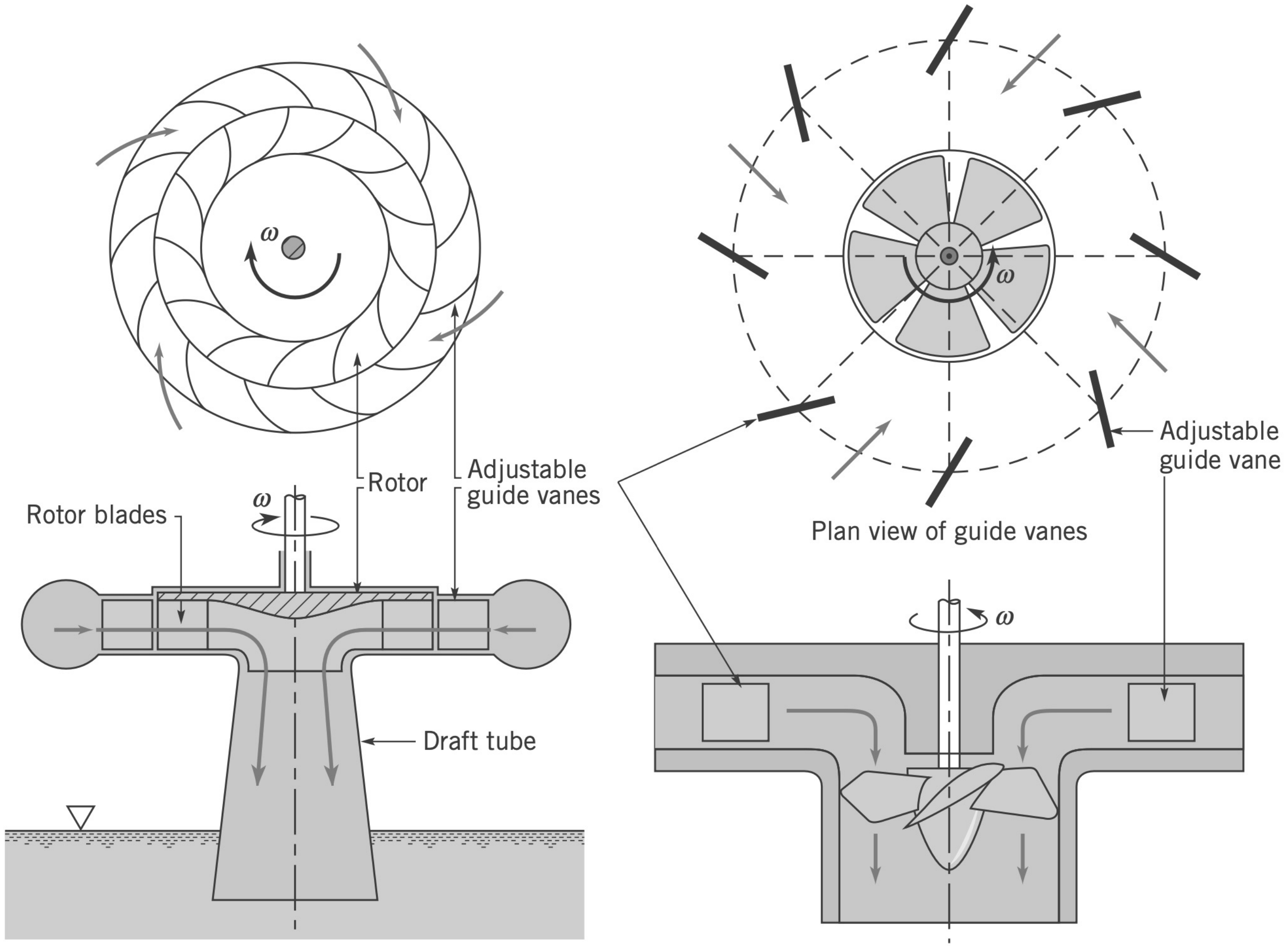
Reaction turbines are best suited for **higher flow rates** and **lower head** situations.

Reaction Turbines

As with pumps, turbines are manufactured in a variety of configurations—radial-flow, mixed-flow, and axial-flow types.

Typical radial- and mixed-flow hydraulic turbines are called **Francis** turbines, named after James B. Francis, an American engineer.

The Kaplan turbine, named after Victor **Kaplan**, a German professor, is an efficient axial-flow hydraulic turbine with adjustable blades.



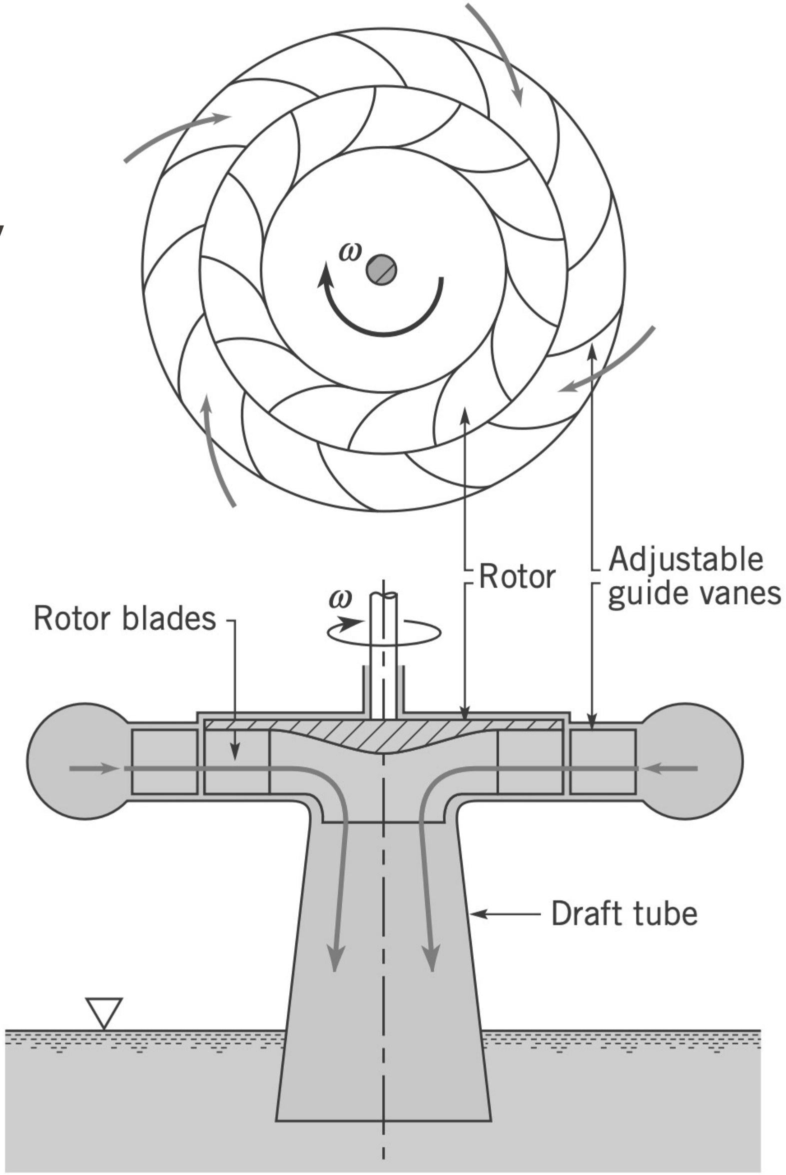
Radial-Inflow Turbine

- Flow across rotor blades has a major **radial** component
- **Adjustable inlet guide vanes** direct water with a **tangential velocity** into the rotor
- Water exits rotor **with no tangential velocity component**
- Rotor:
  - **Decreases angular momentum** of the fluid
  - Fluid exerts **torque on rotor** in direction of rotation
  - Rotor **extracts energy from fluid**
- **Euler turbomachine equation** and **power equation** apply, similar to a centrifugal pump

$$T_{\text{shaft}} = -\dot{m}_1 \left(r_1 V_{\theta 1}\right) + \dot{m}_2 \left(r_2 V_{\theta 2}\right)$$

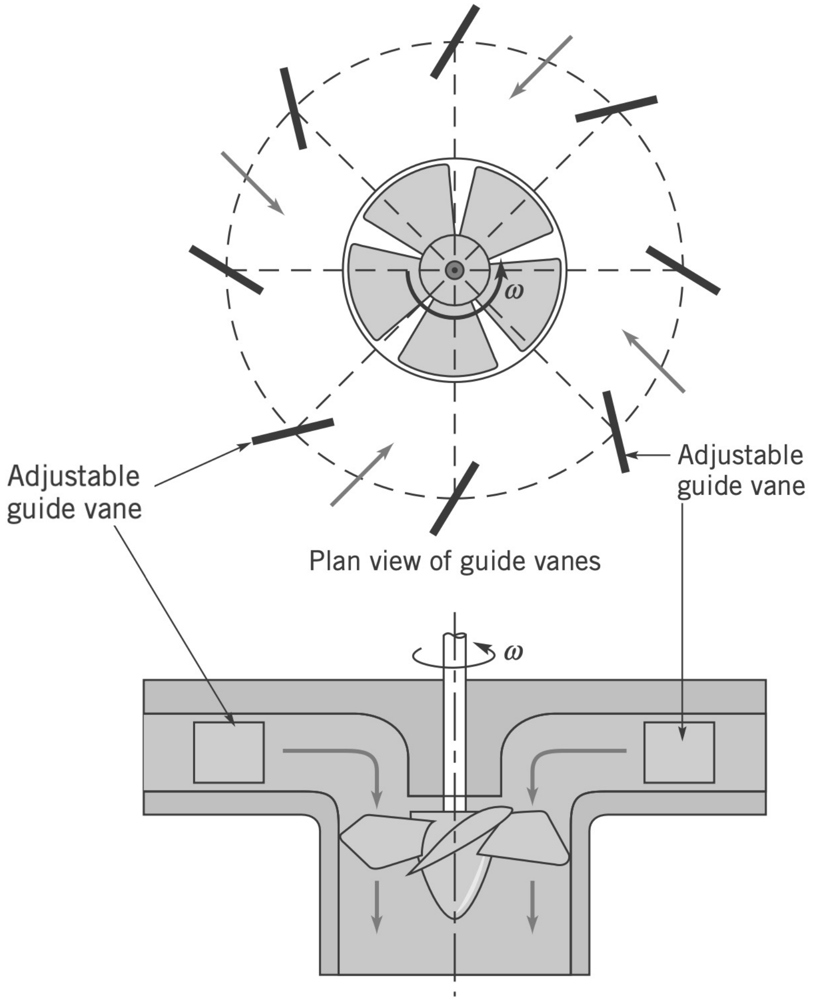
$$\dot{W}_{\text{shaft}} = -\dot{m}_1 \left(U_1 V_{\theta 1}\right) + \dot{m}_2 \left(U_2 V_{\theta 2}\right)$$

$$w_{\text{shaft}} = -\left(U_1 V_{\theta 1}\right) + \left(U_2 V_{\theta 2}\right)$$



Axial-Flow Kaplan Turbine

- Fluid flows through **inlet guide vanes (wicket gates)**, gaining **tangential velocity (vortex/swirl)**
- Flow across rotor has a major **axial** component
- Both **inlet guide vanes** and **turbine blades are adjustable** for optimal performance
- Adjustment accommodates:
    - Changes in **operating head** (seasonal variations)
    - Variations in **flow rate** through the rotor



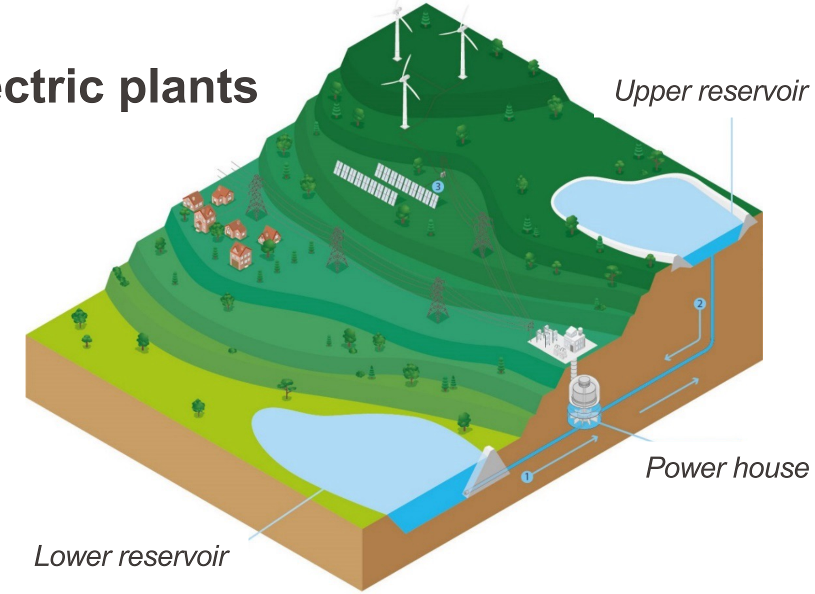
Pumps vs. Turbines

- **Pumps and turbines are "inverse" machines**
- **Pumps add energy** to the fluid
- **Turbines remove energy** from the fluid

- Example:
  - Propeller on an **outboard motor (pump)** vs. propeller on a **Kaplan turbine**
  - **Geometrically similar**, but perform **opposite tasks**
  - Similar comparison: **centrifugal pumps vs. Francis turbines**

Pump storage

- Some large **pump/turbines** are used in **pumped storage hydroelectric plants**
- Run as **turbines during high-power demand** (day)
- Run as **pumps during low-power demand** (night)
- Used to **resupply upstream reservoir**
- Often, **each pump type has a corresponding turbine type**



Dimensionless numbers

As with pumps, incompressible flow turbine performance is often specified in terms of appropriate dimensionless parameters. The flow coefficient, the head coefficient, and the power coefficient are defined in the same way for pumps and turbines

Flow coefficient : $$C_Q = \frac{Q}{\omega D^3}$$

Head coefficient : $$C_H = \frac{g h_a}{\omega^2 D^2}$$

Power coefficient : $$C_{\mathscr{P}} = \frac{\dot{W}_{\text{shaft}}}{\rho \omega^3 D^5}$$

On the other hand, turbine efficiency, η, is the inverse of pump efficiency.
That is, the efficiency is the ratio of the **shaft power output** to the **power available in the flowing fluid**:

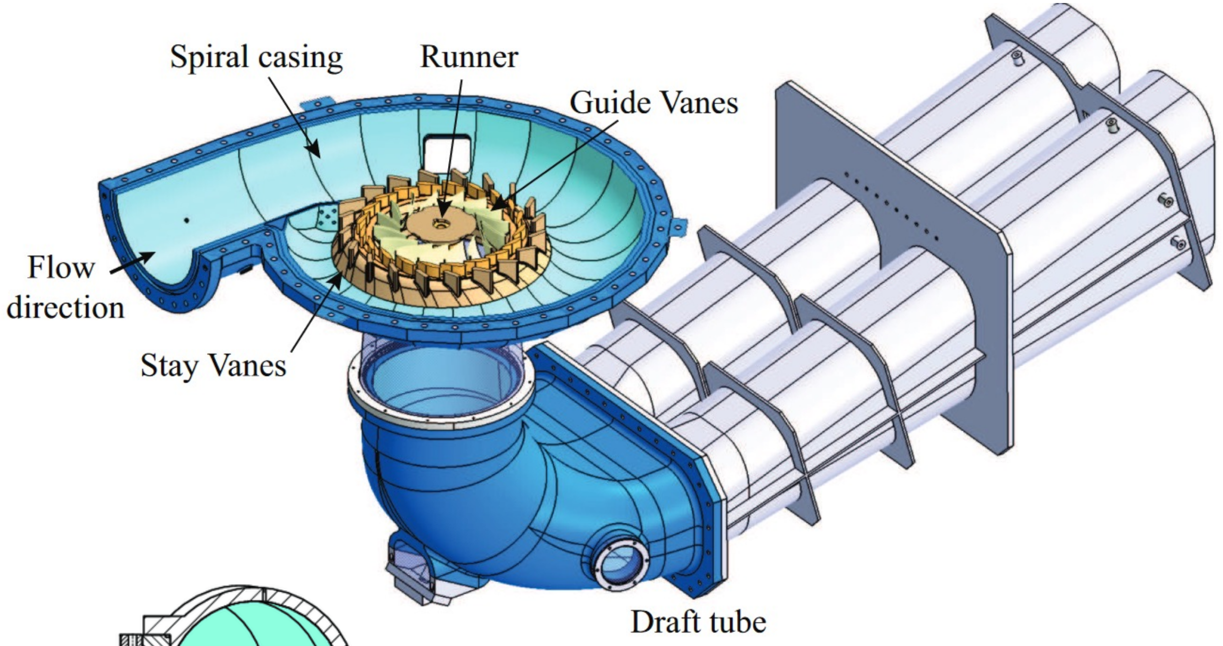
$$\eta_{\text{turbine}} = \frac{\dot{W}_{\text{shaft}}}{P_f} \qquad \eta_{\text{pump}} = \frac{P_f}{\dot{W}_{\text{shaft}}}$$

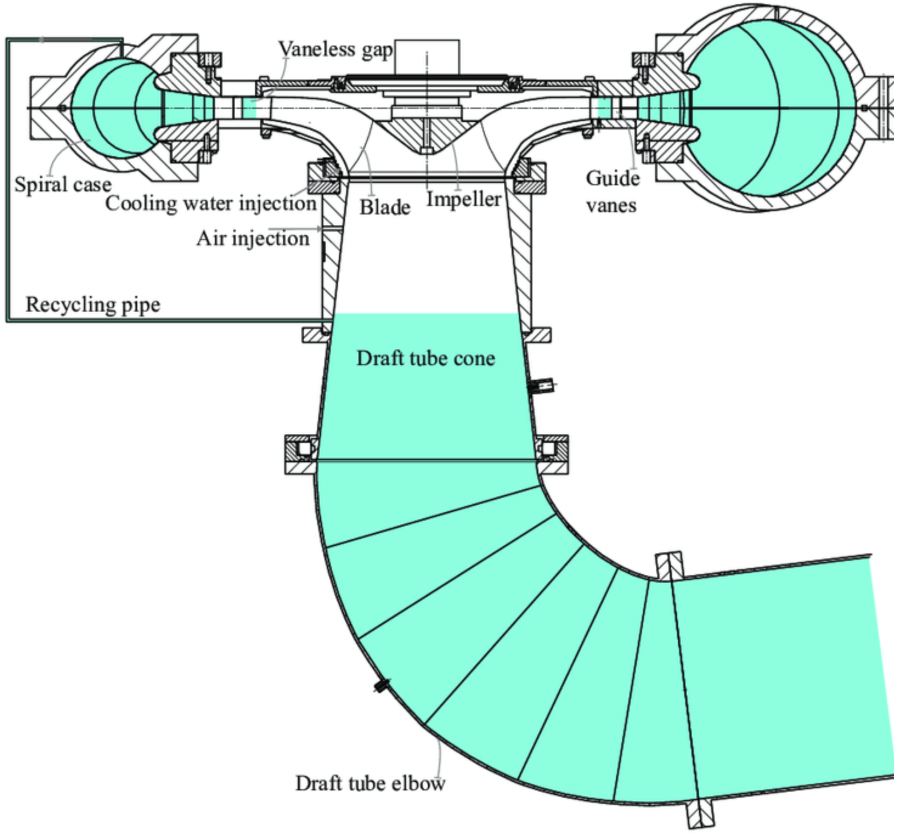
$$P_f = \gamma Q h_a$$

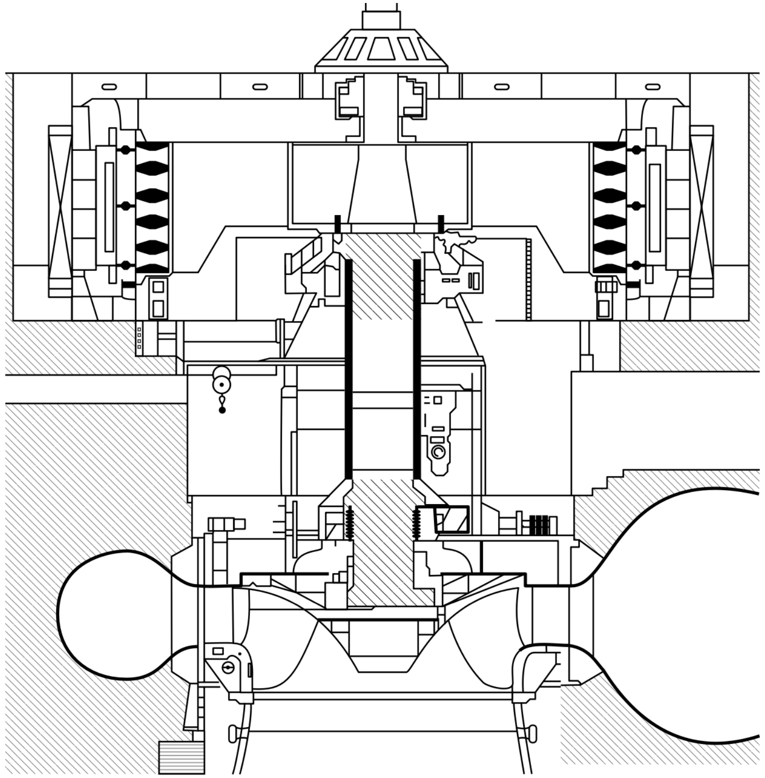
Hydraulic Turbines – Reaction turbines
Francis turbine

Francis Turbine

- **Main components:**
  - Spiral casing
  - Stay vanes
  - Wicket gates (Distributor)
  - Runner
  - Draft tube

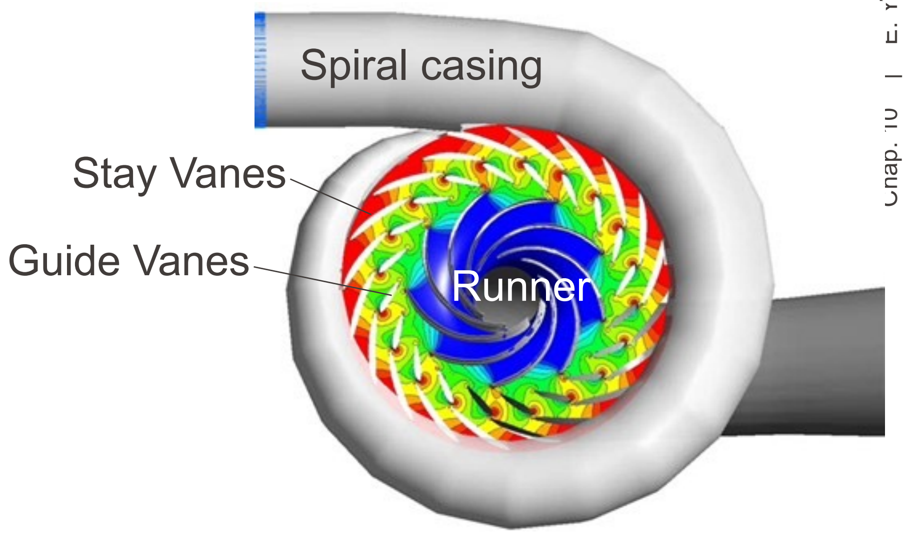






Francis Turbine

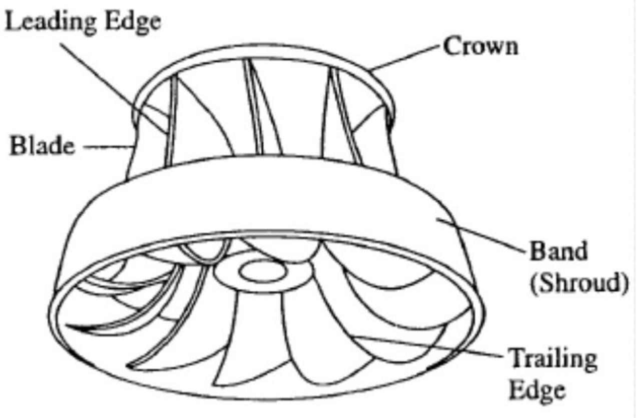
- **Spiral casing**:
  - Connects the turbine to the incoming flow (from the penstock)
  - Creates a uniform and pre-rotating flow
- **Stay vanes**:
  - Set of fixed vanes: Direct the flow towards the runner
- **Wicket gates (Guide vanes)**:
  - Set of adjustable vanes: Direct the flow further and adjust the flowrate (from ~0% to 100%)
  - Actioned by a servomotor with the help of a gates ring



Francis Turbine

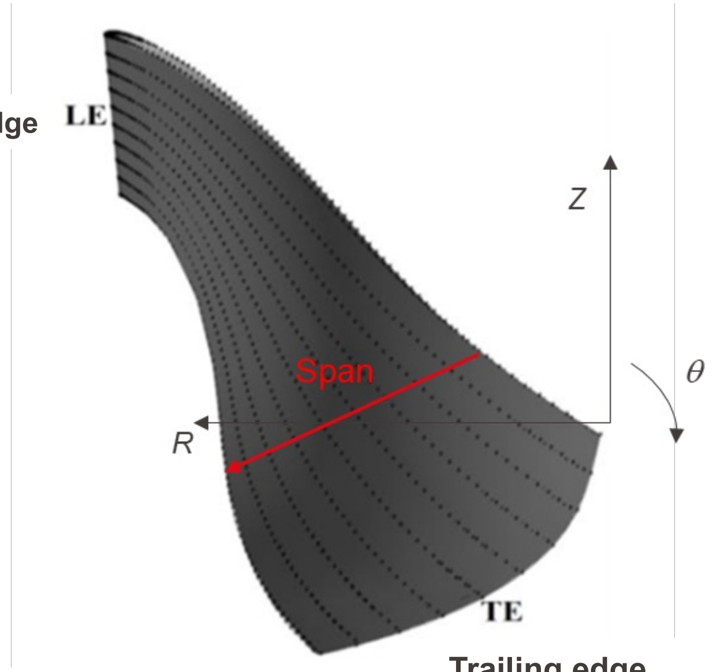
- **Runner:**
  - The most sensitive component, made of a set of sophisticated 3D blades, a crown and a band (shroud)
  - Specific design for every (large) project (Nominal head and flowrate)
  - Highly efficient: more than 95%
  - At optimum conditions, the flow leaves the runner axially. Otherwise, a swirl develops at the runner outlet

- **Draft Tube:**
  - Connects the turbine to the downstream pipe
  - Raises the pressure and slow down the flow

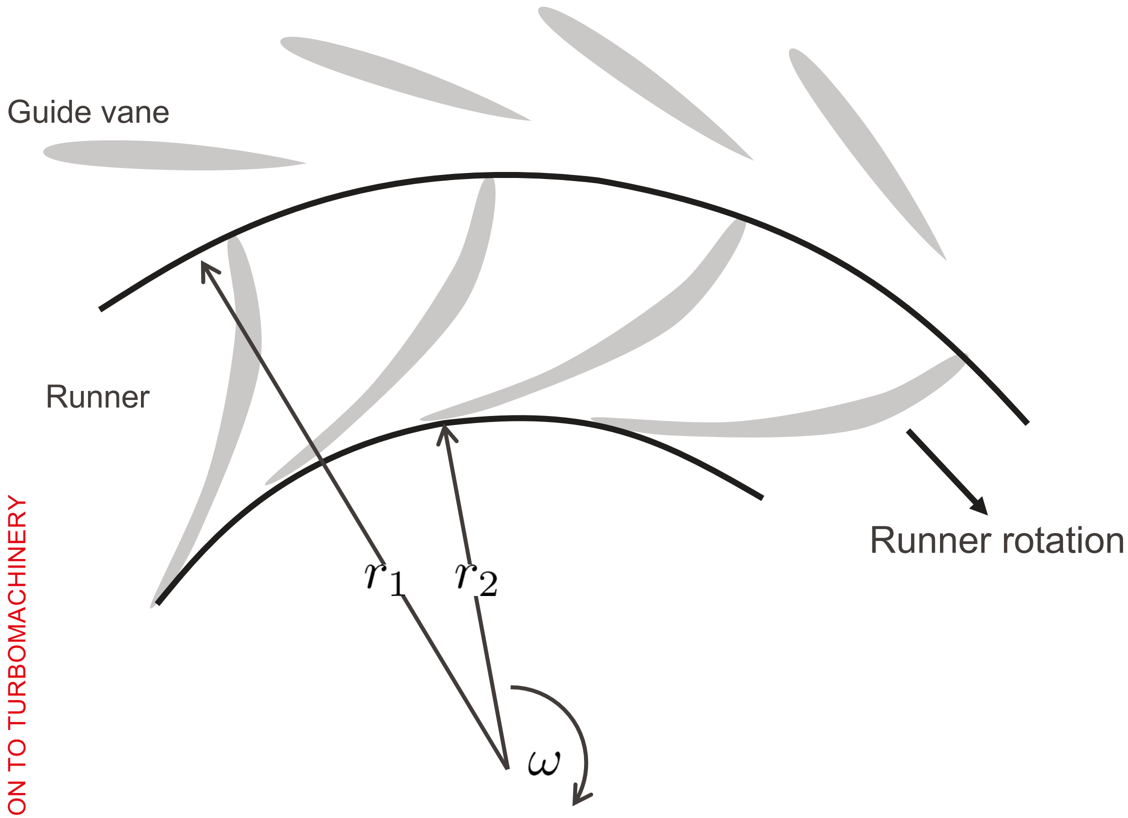


Francis-turbine runner (schematic sketch)

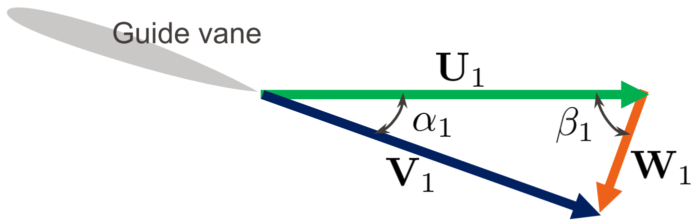
Francis Turbine – Velocity triangle



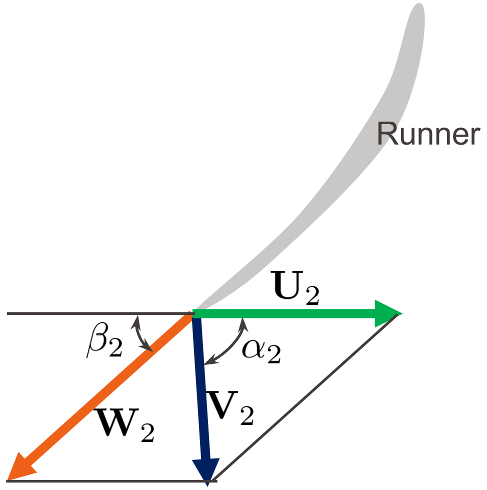
Francis Turbine



- Velocity triangle at the runner inlet



- Velocity triangle at the runner outlet



$\alpha_1 = (\widehat{\overrightarrow{V_1}, \overrightarrow{U_1}})$: imposed by the guide vanes (trailing edge)
$\beta_2 = (\widehat{\overrightarrow{W_2}, \overrightarrow{U_2}})$ is imposed by the runner blades (trailing edge)
β_1 depends on the blade inlet geometry and operating conditions
α_2 depends on the blade inlet geometry and operating conditions

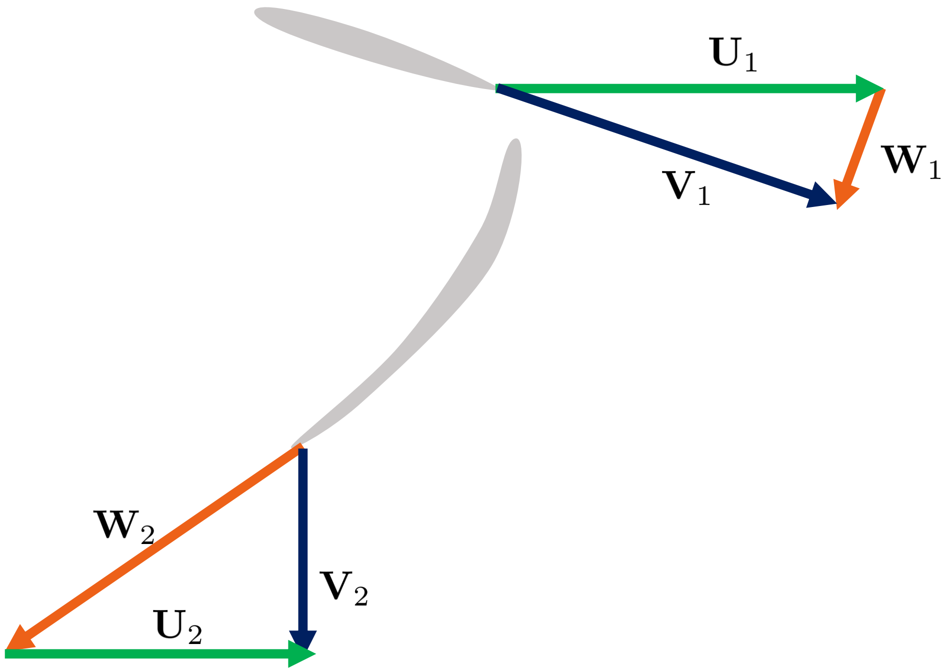
Francis Turbine

In most simple analyses of the Francis turbine it is assumed that there is no exit swirl.

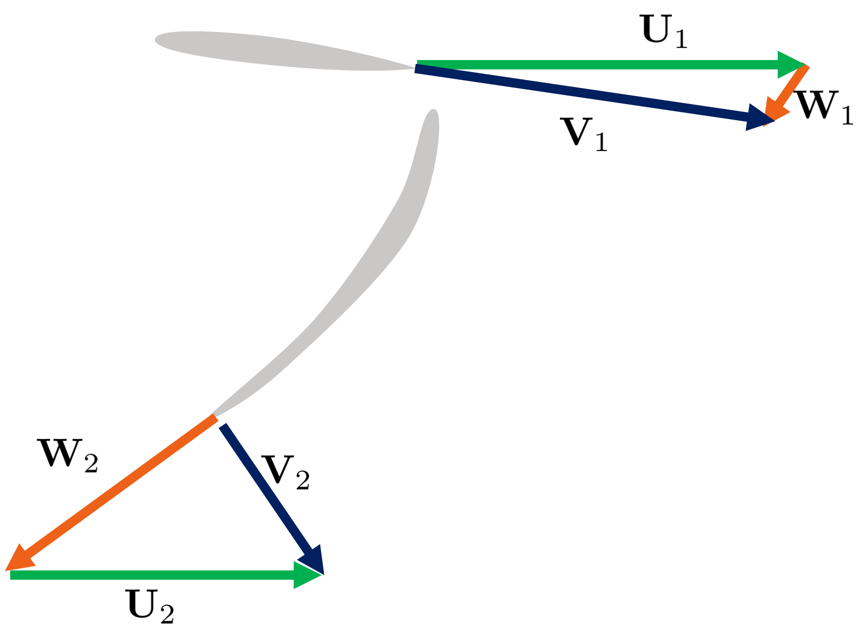
When a Francis turbine is required to operate at part load, the power output is reduced by swiveling the guide vanes to restrict the flow, i.e., Q is reduced, while the blade speed is maintained constant.

The relative flow at runner entry is at a high incidence and at runner exit the absolute flow has a large component of swirl. Both of these flow conditions give rise to high head losses.

Design point operation



Part load operation



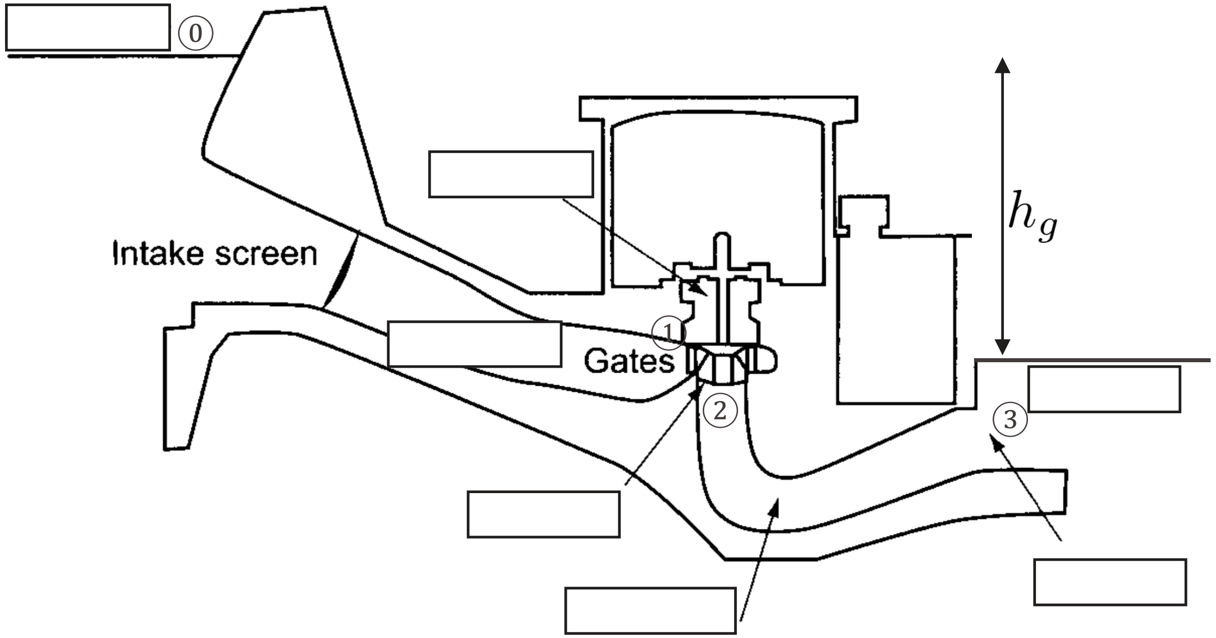
Francis Turbine

The rule also applies to Kaplan turbine

$$\frac{p_1}{\gamma} + \frac{V_1^2}{2g} + z_1 \pm h_s - \sum h_L = \frac{p_2}{\gamma} + \frac{V_2^2}{2g} + z_2$$

If the flow at runner exit is without swirl ($V_{\theta 2} \simeq 0$) then the shaft work per unit mass (specific work) reduces to

$$w_{\text{shaft}} = -(U_1 V_{\theta 1}) + (U_2 V_{\theta 2}) = -(U_1 V_{\theta 1})$$



Then, the shaft head, h_s:

Energy equation between 0 and 3

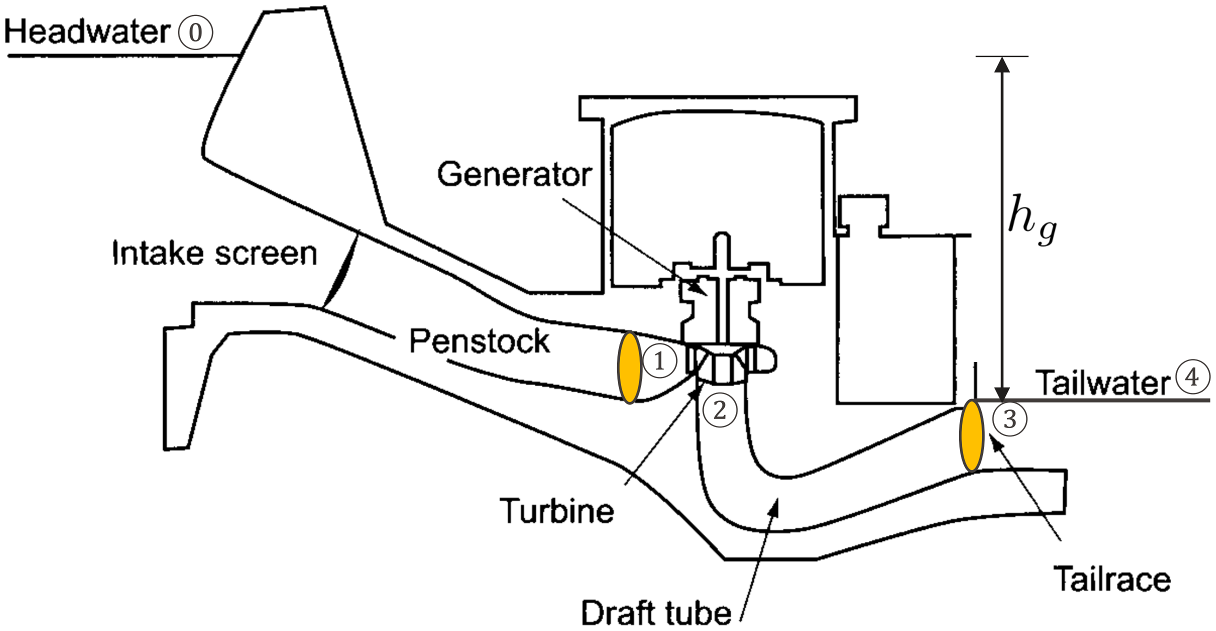
Losses in the flow passage
h_{LP} : the loss of head due to friction in penstock
h_{LV} : the loss of head due to friction in the volute and guide vanes
h_{LR} : the loss of head due to friction in runner
h_{LD} : the loss of head due to friction in draft tube

EPFL

Francis Turbine

The rule also applies to Kaplan turbine

Efficiency of turbine : $\eta = \eta_m \eta_h \eta_v$



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Pump performance characteristics

- Overall efficiency $\eta = \dfrac{\text{power gained by the fluid}}{\text{shaft power driving the pump}} = \dfrac{P_f}{\dot{W}_{\text{shaft}}}$

= ratio of power actually gained by the fluid to the shaft power supplied

- Hydraulic losses: Skin friction, flow separation, 3D and unsteady effects
  → Hydraulic efficiency η_h
- Mechanical losses: bearing and sealing losses
  → Mechanical efficiency η_m
- Volumetric losses: flow leakage components
  → Volumetric efficiency η_v

$$\eta = \eta_h \eta_m \eta_v$$

$$\eta_h = \frac{|w_{\text{shaft}}|}{gH_E} = \frac{|-U_1 V_{\theta 1} + U_2 V_{\theta 2}|}{gH_E} = \frac{U_1 V_{\theta 1}}{gH_E}$$

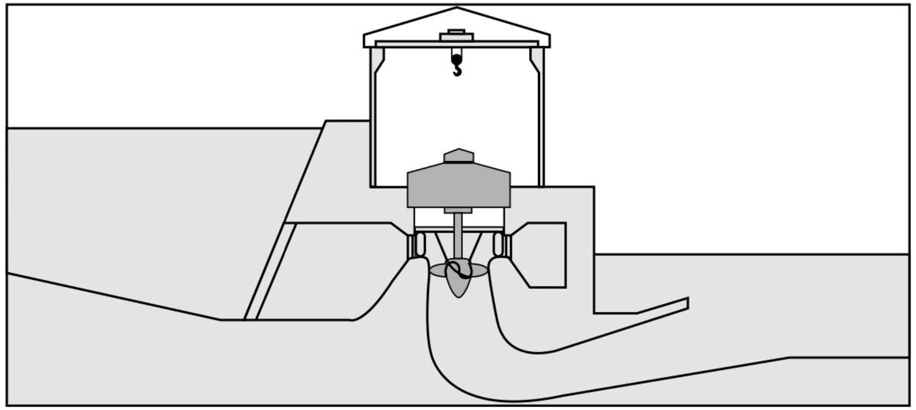
H_E is the total head available at the turbine **inlet** relative to the surface of the tailrace → $H_E = h_g - h_{LP}$

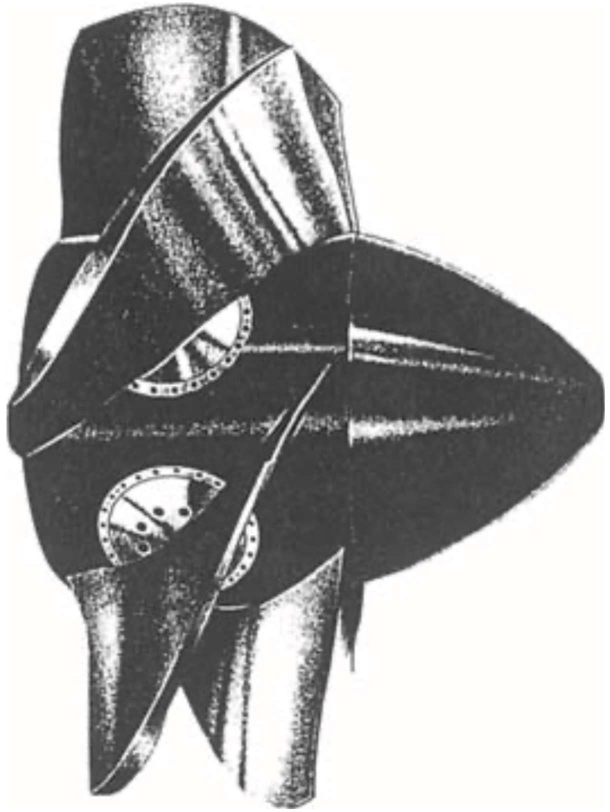
$$\eta_h = \frac{\text{shaft power driving the turbine}}{\text{power gained by the fluid}} = \frac{\dot{W}_{\text{shaft}}}{P_f}$$

$$P_f = \gamma Q h_a$$

Hydraulic Turbines – Reaction turbines
Kaplan and Bulb turbines

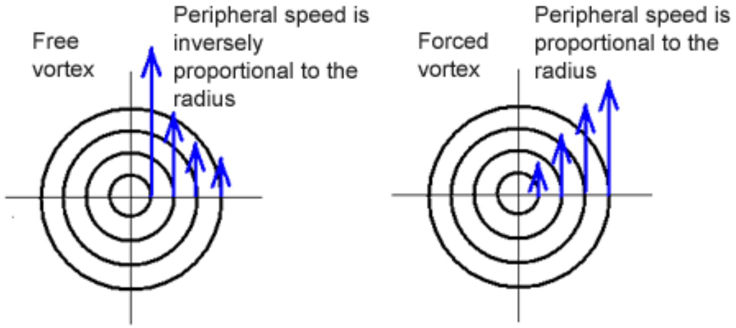
Kaplan turbine





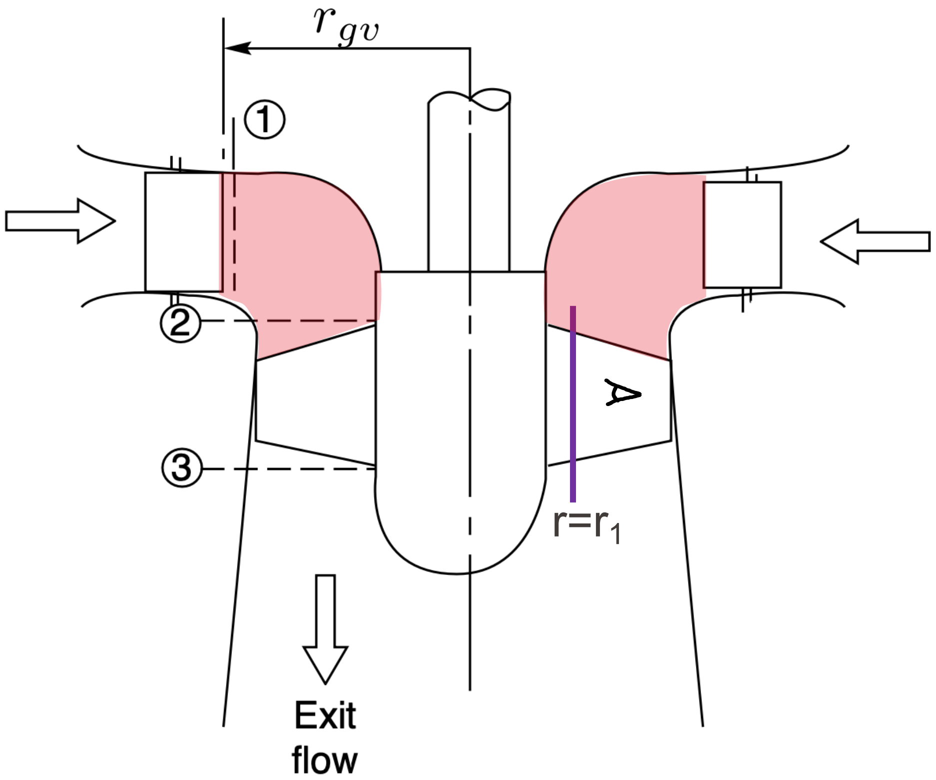
The flow leaving the guide vanes is forced by the shape of the passage into an axial direction and the swirl becomes essentially a **free vortex**:

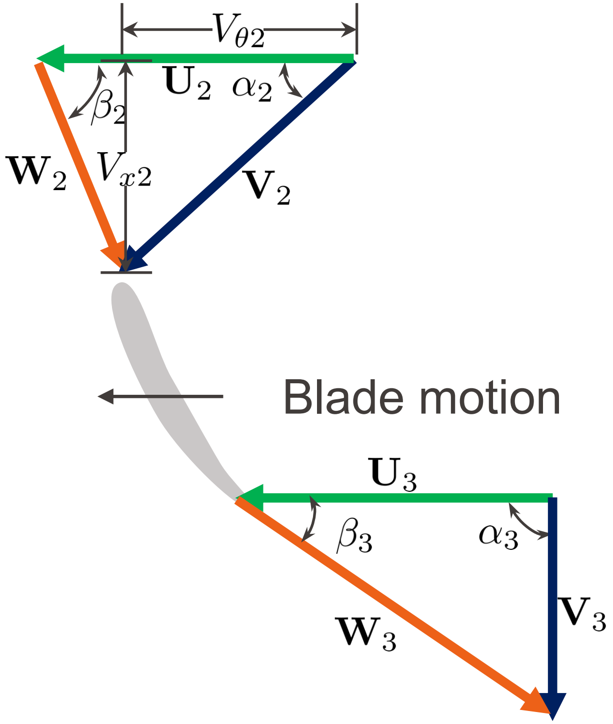
→ Angular momentum is constant over the radius
→ Small *r*, large V_θ
→ Large *r*, small V_θ



Kaplan turbine

Free vortex $rV_\theta = cnst. \rightarrow V_\theta = \frac{K}{r}$





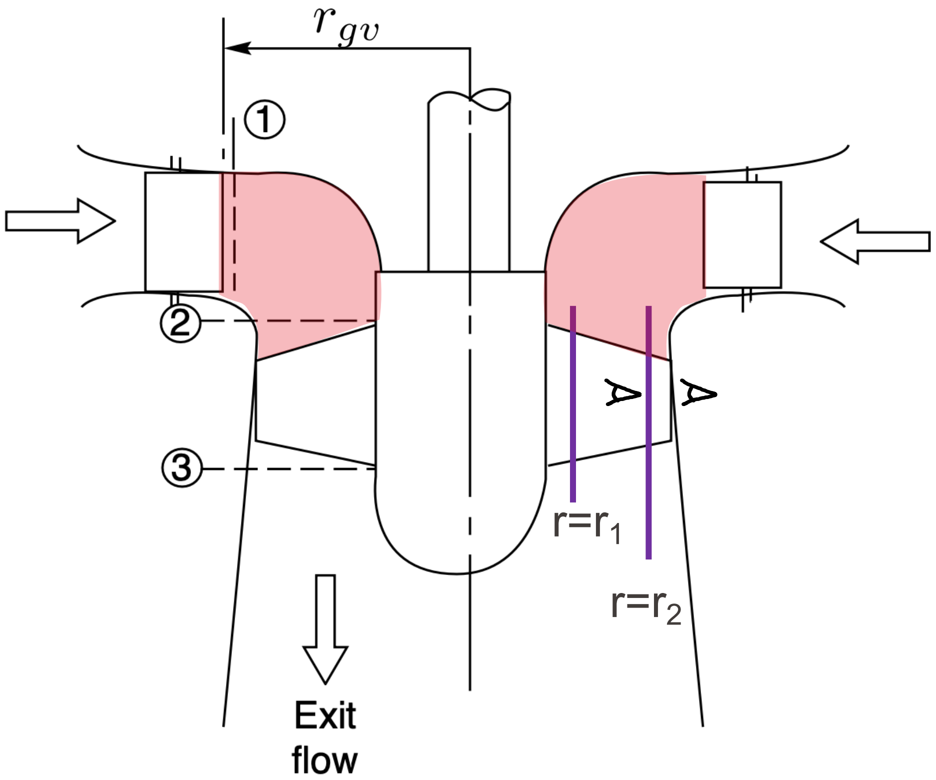
Blade angles w.r.t. horizontal line

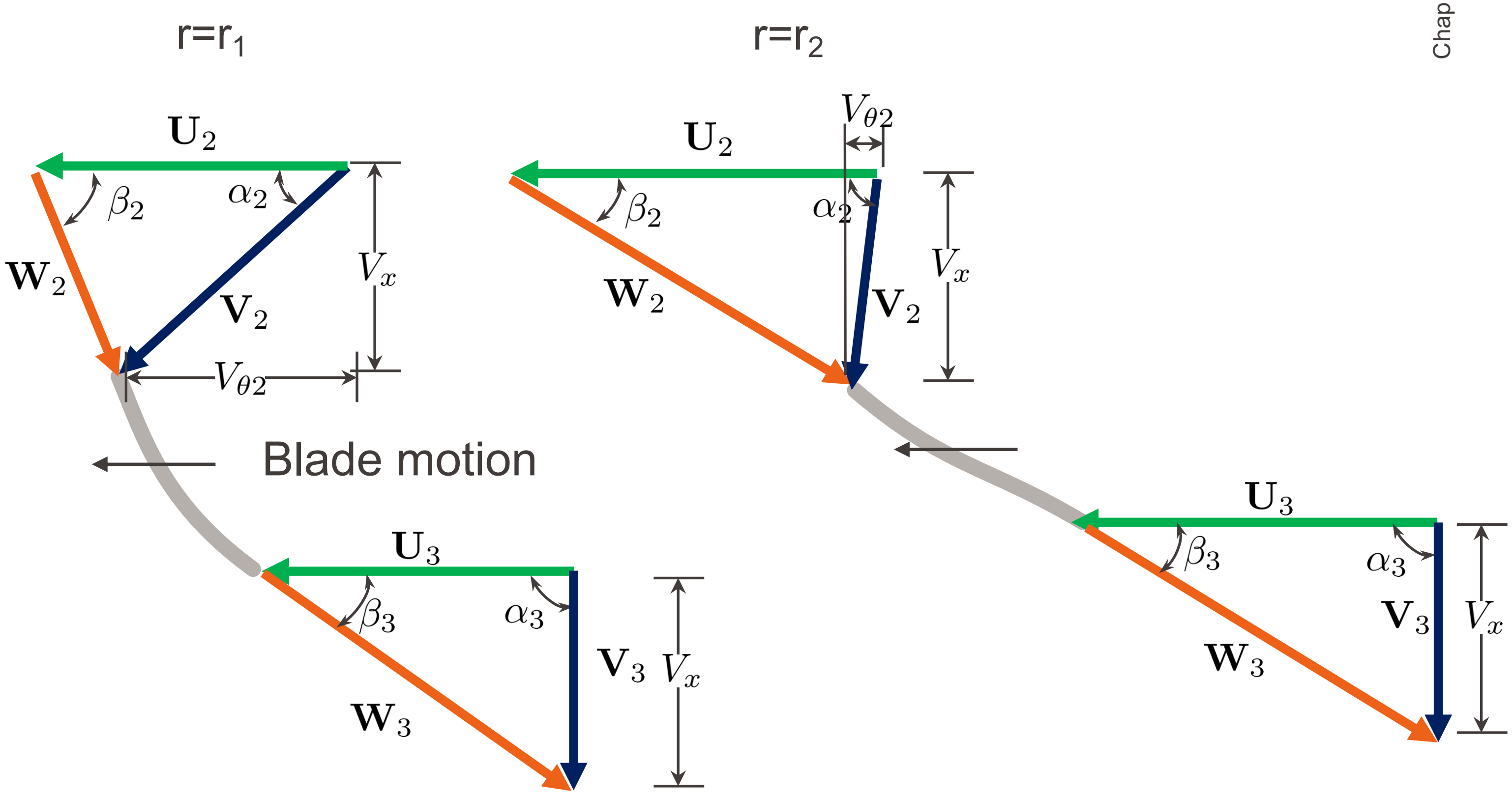
Well-designed blade $\alpha_3 = \pi/2$, $V_{\theta 3}=0$
$\rightarrow V_3=V_x$

Kaplan turbine

$$V_\theta = \frac{K}{r}$$

Free vortex, axial velocity constant





Kaplan turbine

Exercise

$$\rho = 1000\ \mathrm{kg/m^3},\ \eta_h = \frac{\dot{W}_{\text{shaft}}}{\gamma Q h_a},\ \eta_h = \frac{U_1 V_{\theta 1}}{g H_E}$$

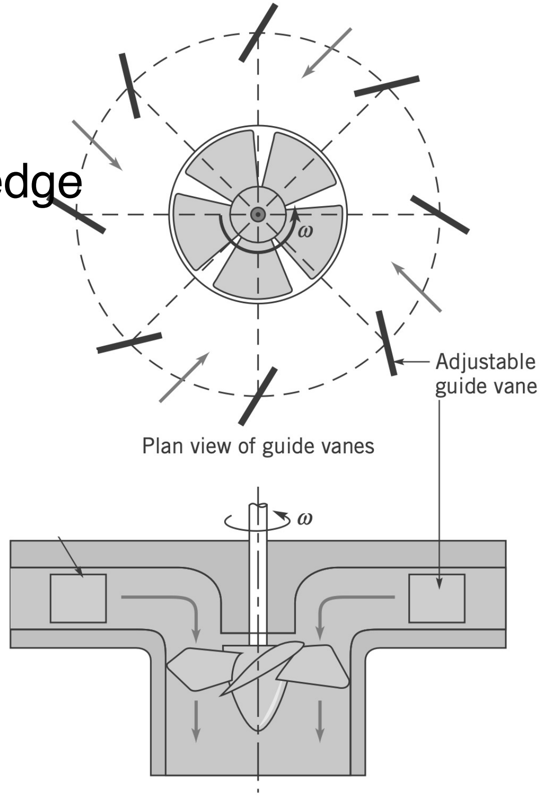
A small-scale Kaplan turbine has a power output of 8 MW, an available head (H_E) at turbine entry of 13.4 m, and a rotational speed of 200 rev/min. The inlet guide vanes have a length of 1.6 m and the diameter at the trailing edge surface is 3.1 m. The runner diameter is 2.9 m and the hub–tip ratio ($=D_{hub}/D_{tip}$) is 0.4. Assuming the hydraulic efficiency is 92% (ignore mech. & volumetric losses) and the runner design is "free-vortex", determine

(i) The radial component of velocity at exit from the guide vanes

(ii) The component of axial velocity at the runner and the azimuthal velocity of the runner edge

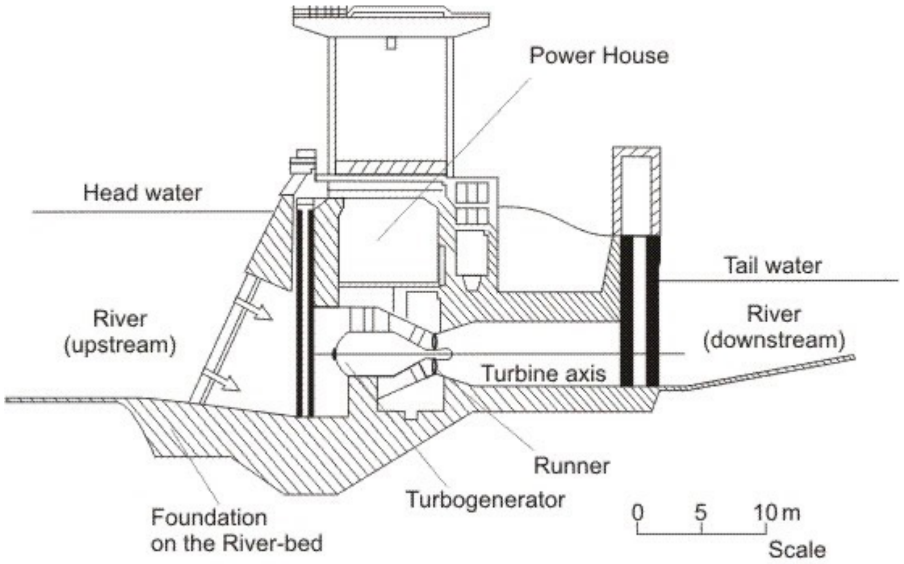
(iii) the absolute and relative flow angles upstream and downstream of the runner at the tip

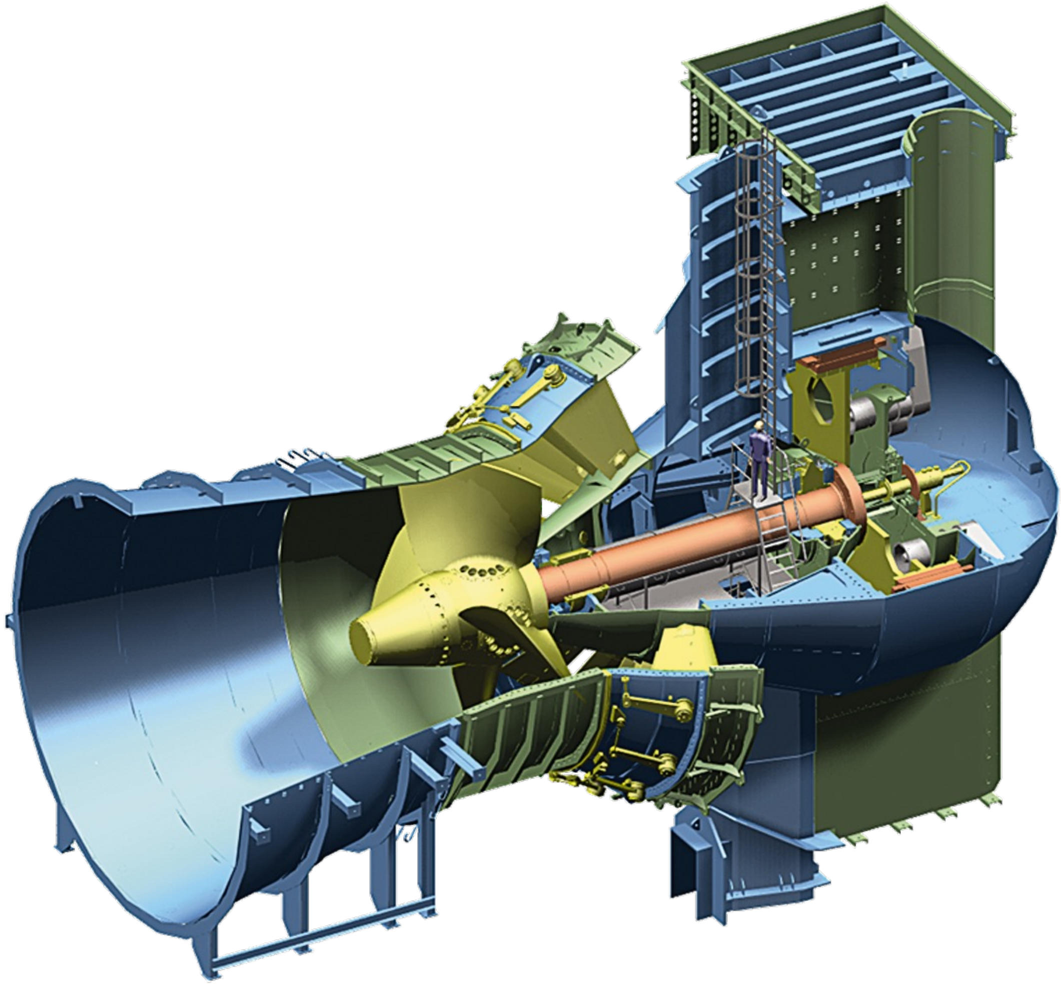
From the free vortex relation, what is the azimuthal velocity of the outlet of the guide vane?



Bulb turbine

- Kaplan turbine in horizontal configuration. Suited for very low heads and high flowrates
- The turbine and the generator are fitted inside a bulb with fully axial flow
  → low construction cost
- No spiral casing, no stay vanes
- Straight draft tube → higher efficiency



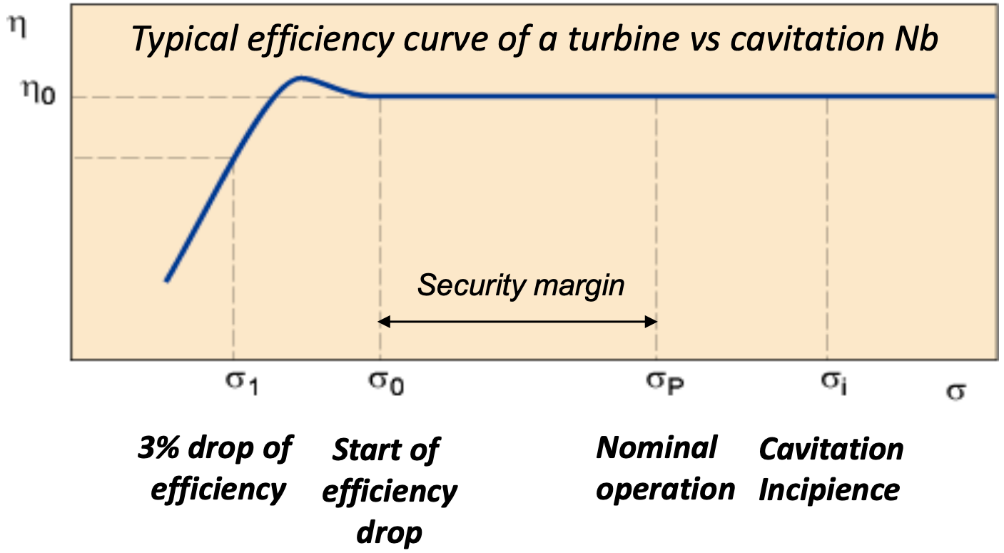


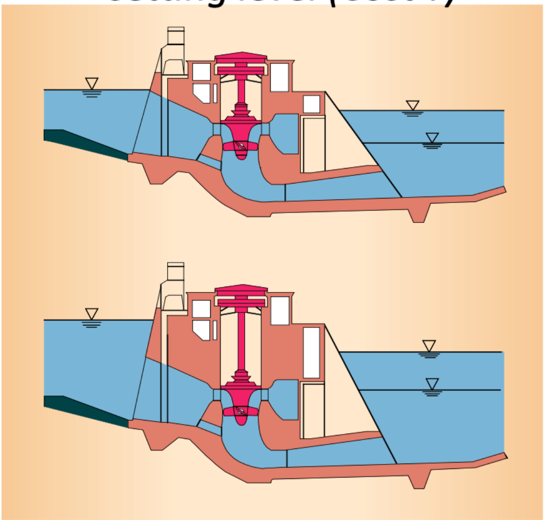
Recall - Cavitation

Cavitation Effects

- **Effects of cavitation:**
  1. Alteration of hydrodynamic performances:
  The presence of the gas phase within a flowing liquid causes an increase of drag and a decrease of lift

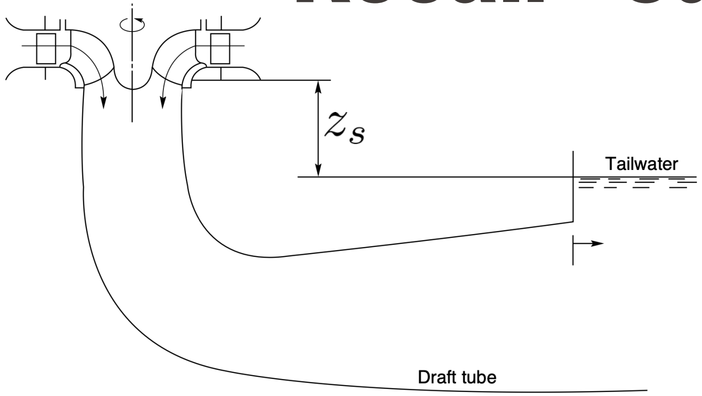
Solution: Increase of the setting level (Cost ?)





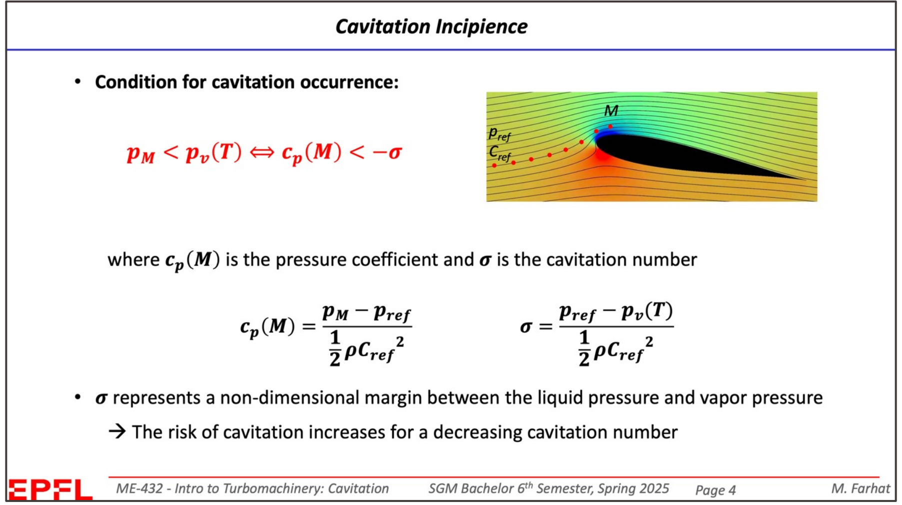
As for submarines, a hydraulic turbine may be placed deeper in earth to increase the pressure and avoid cavitation. Nevertheless, this comes with an increase of the construction cost.

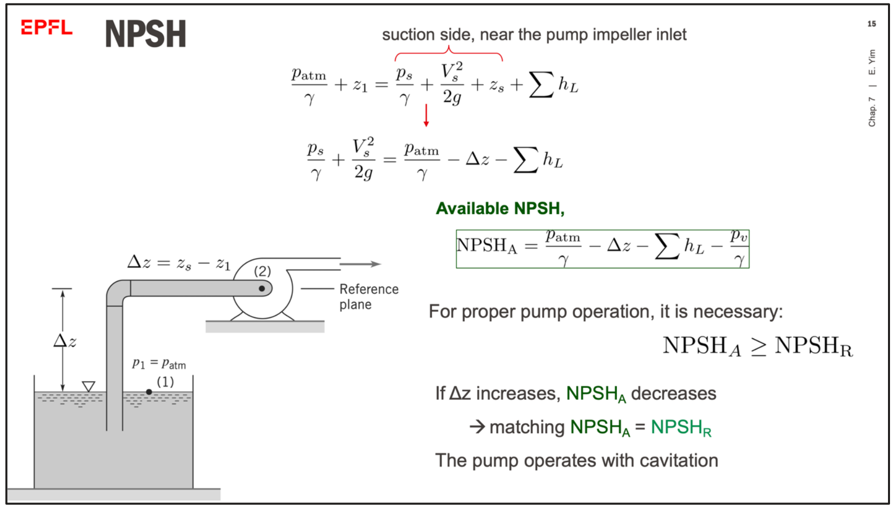
Recall - Cavitation



Thoma coefficient : $\sigma = \dfrac{\text{NPSH}_A}{H_E}$

Note! It is not the same σ from Ch9 with the dynamic pressure, it shows more local behaviour near the blades. Thoma number is for a global hydropower plant location.





NPSH_A : the amount of head needed to avoid cavitation

The net positive suction pressure (NPSH_A) is defined as the sum of the **static pressure head** and the **dynamic head** minus the **vapor pressure head** of water at the ambient temperature

$$\text{NPSH}_A = \frac{p_s - p_v}{\gamma} + \frac{V_s^2}{2g} \longrightarrow \frac{p_{atm} - p_v}{\gamma} - z_s + \sum h_L$$

$$\sigma = \frac{p_{atm} - p_v}{\gamma H_e} - \frac{z_s}{H_e} + \frac{\sum h_L}{H_e}$$

EPFL

Cavitation number

Power specific speed and cavitation number

$$N_s' = \frac{\omega\sqrt{\dot{W}_{\text{shaft}}\ /\rho}}{(gh_a)^{5/4}}$$

A Francis turbine with the effective head of H_E = 80 m and operates N'_s = 1, ignore other losses.

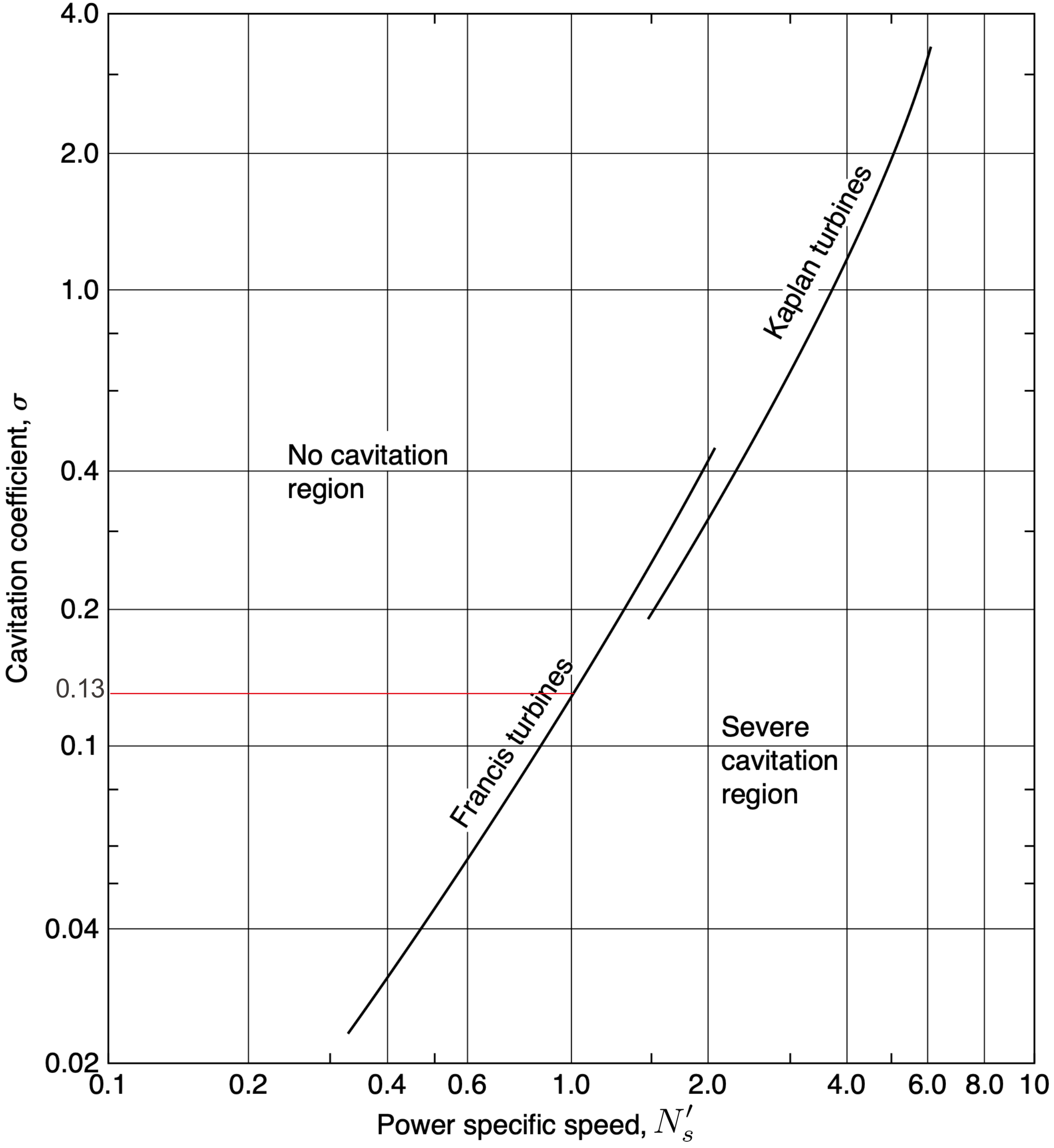
If the level difference of turbine outlet is 5 m, will the cavitation occur?

If so, what will be the critical level difference of the turbine to avoid it?

The water temperature is 30 °C, 101.3 kPa

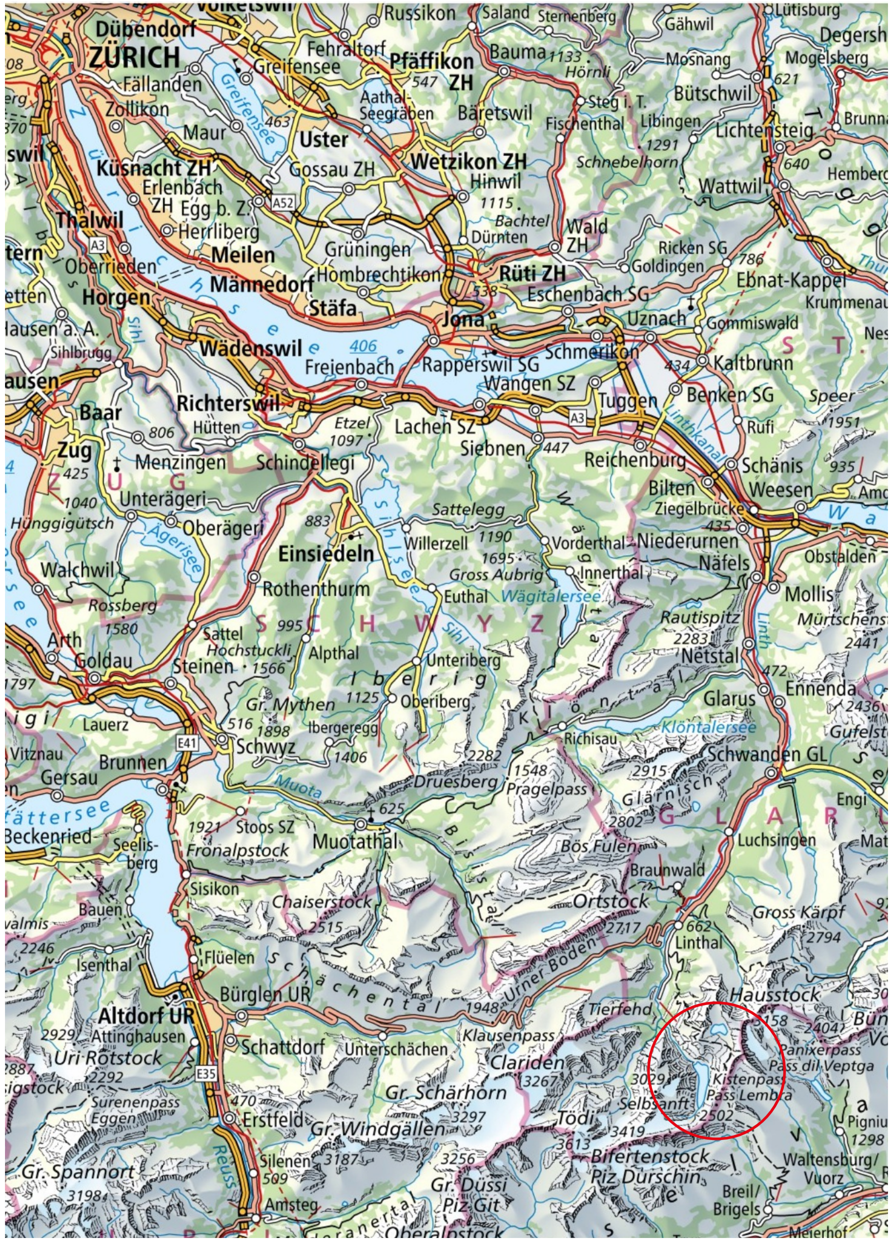
Physical Properties of Water (SI Units)[a]

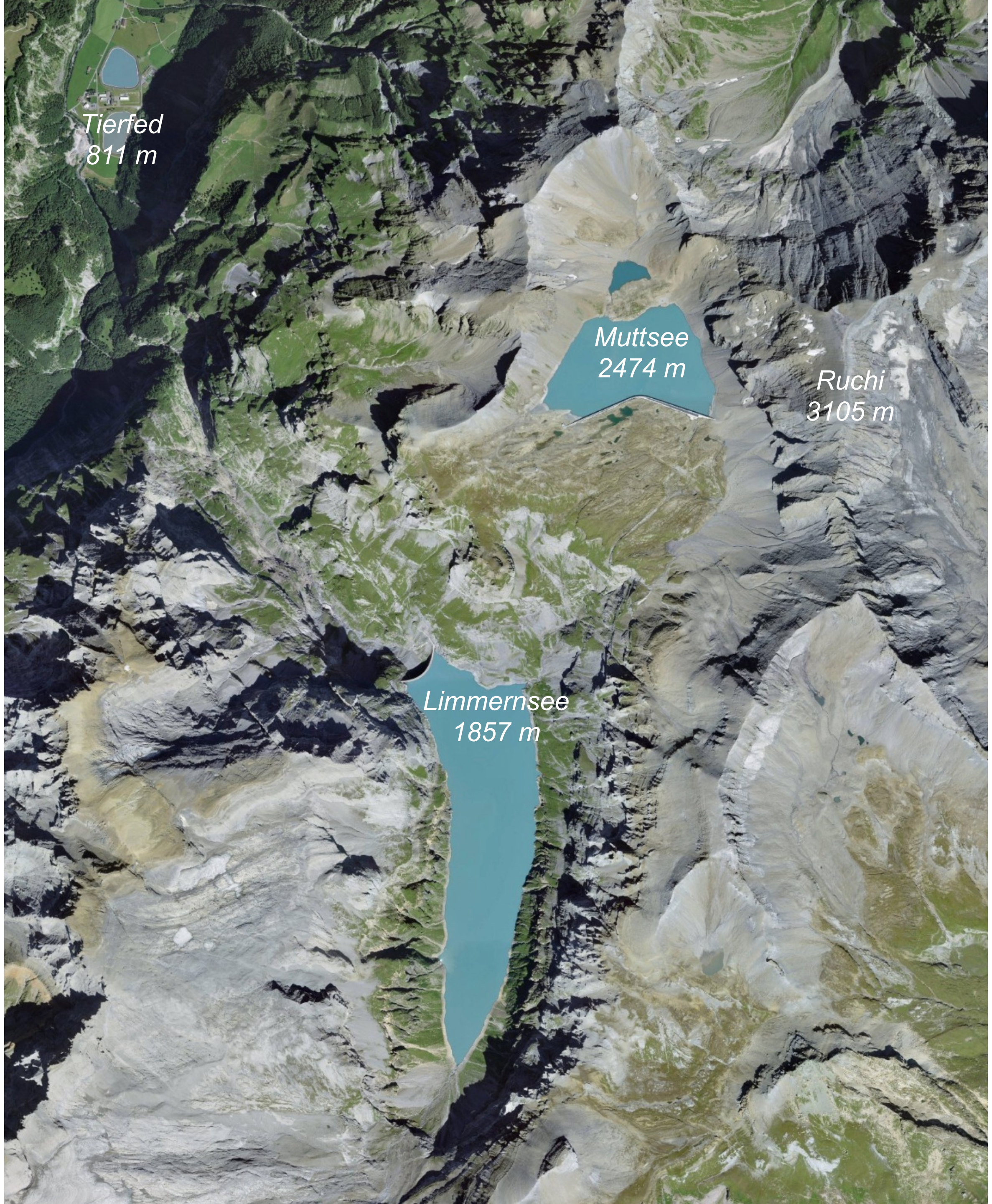
Temperature (°C)	Density, ρ (kg/m^3)	Specific Weight[b], γ (kN/m^3)	Dynamic Viscosity, μ (N·s/m^2)	Kinematic Viscosity, ν (m^2/s)	Surface Tension[c], σ (N/m)	Vapor Pressure, p_v [N/m^2(abs)]
0	999.9	9.806	1.787 E − 3	1.787 E − 6	7.56 E − 2	6.105 E + 2
5	1000.0	9.807	1.519 E − 3	1.519 E − 6	7.49 E − 2	8.722 E + 2
10	999.7	9.804	1.307 E − 3	1.307 E − 6	7.42 E − 2	1.228 E + 3
20	998.2	9.789	1.002 E − 3	1.004 E − 6	7.28 E − 2	2.338 E + 3
30	995.7	9.765	7.975 E − 4	8.009 E − 7	7.12 E − 2	4.243 E + 3

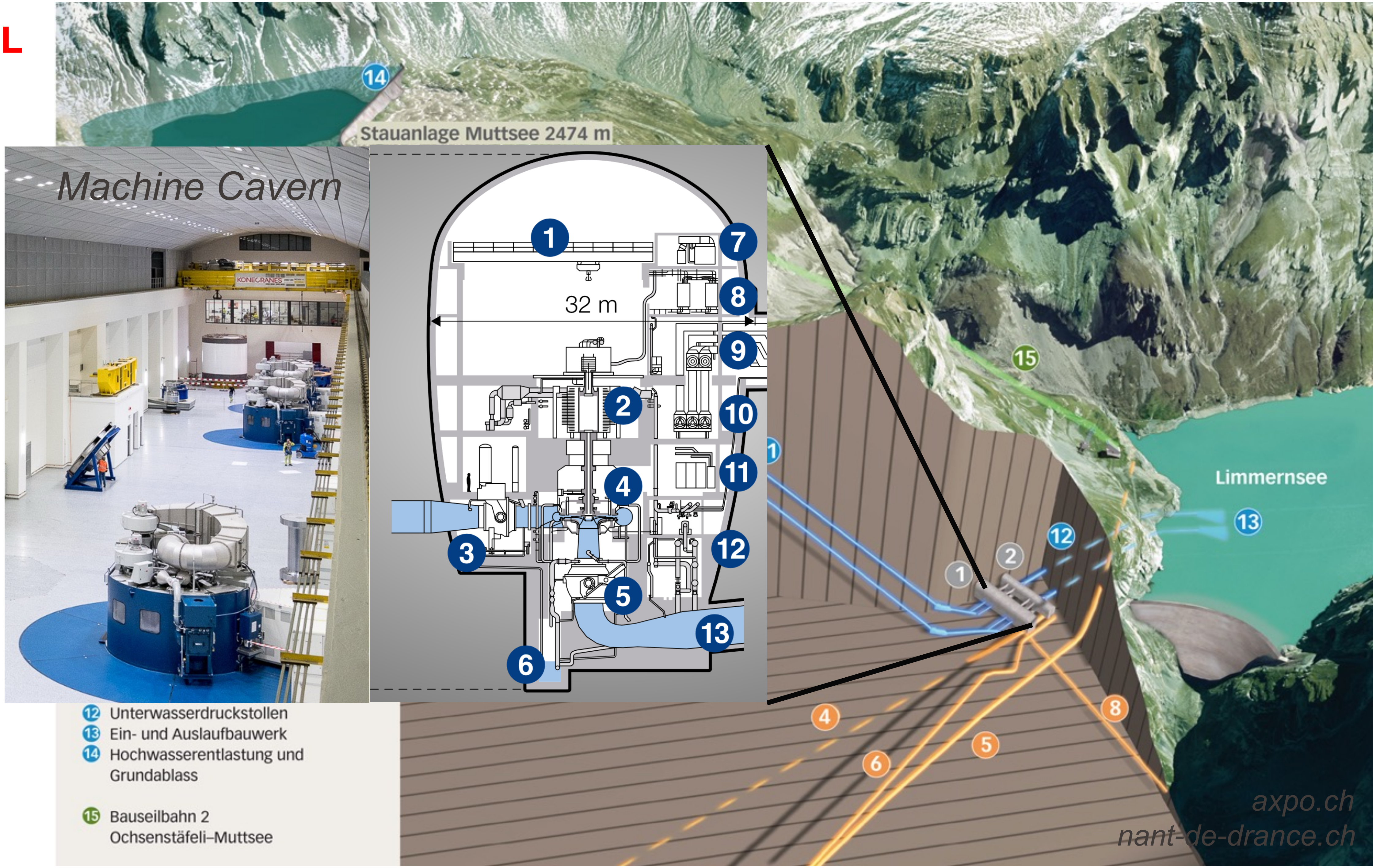


$$\sigma = \frac{p_{\text{atm}} - p_v}{\gamma H_e} - \frac{z_s}{H_e} + \frac{\sum h_L}{H_e}$$

Pump storage



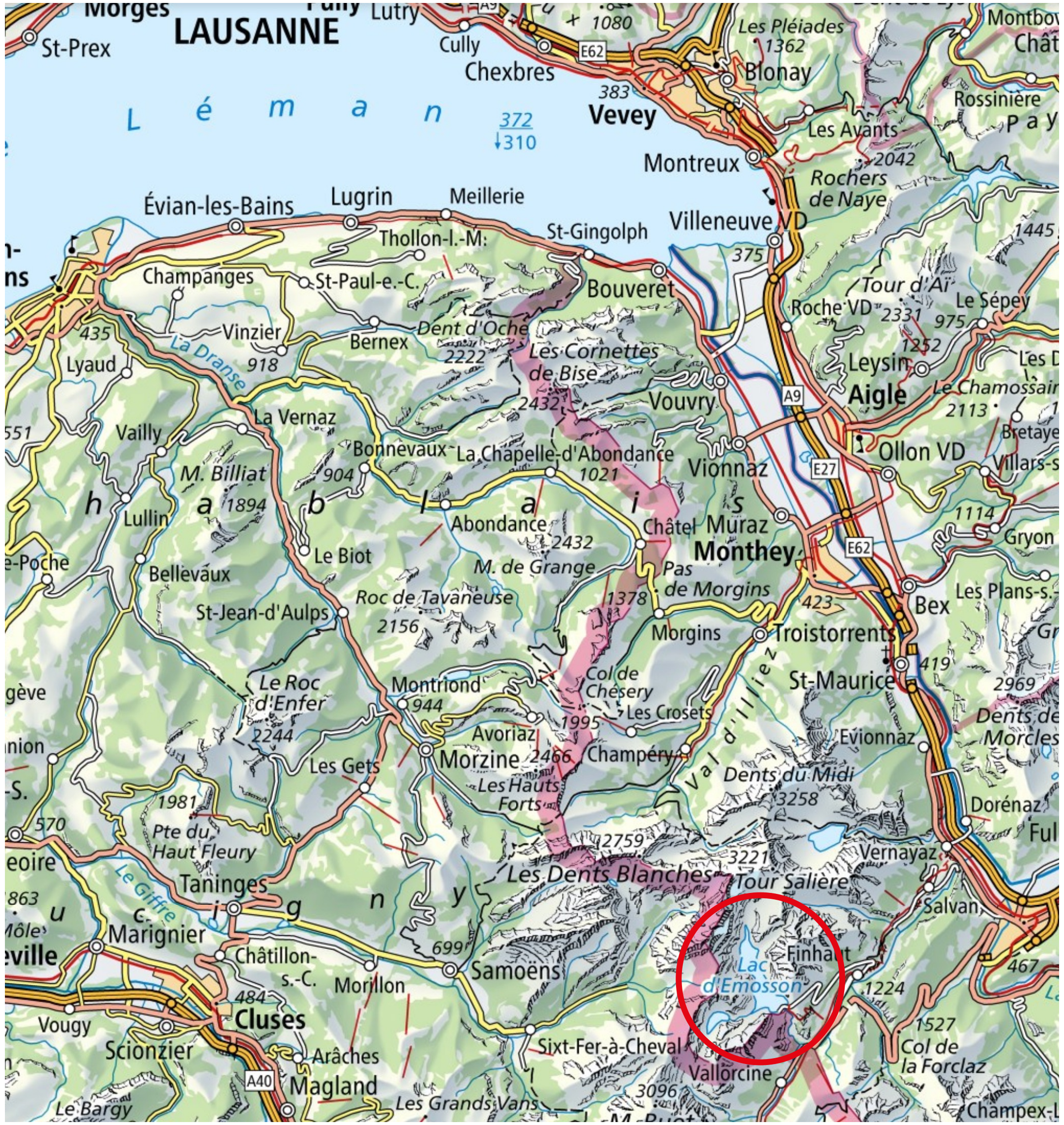


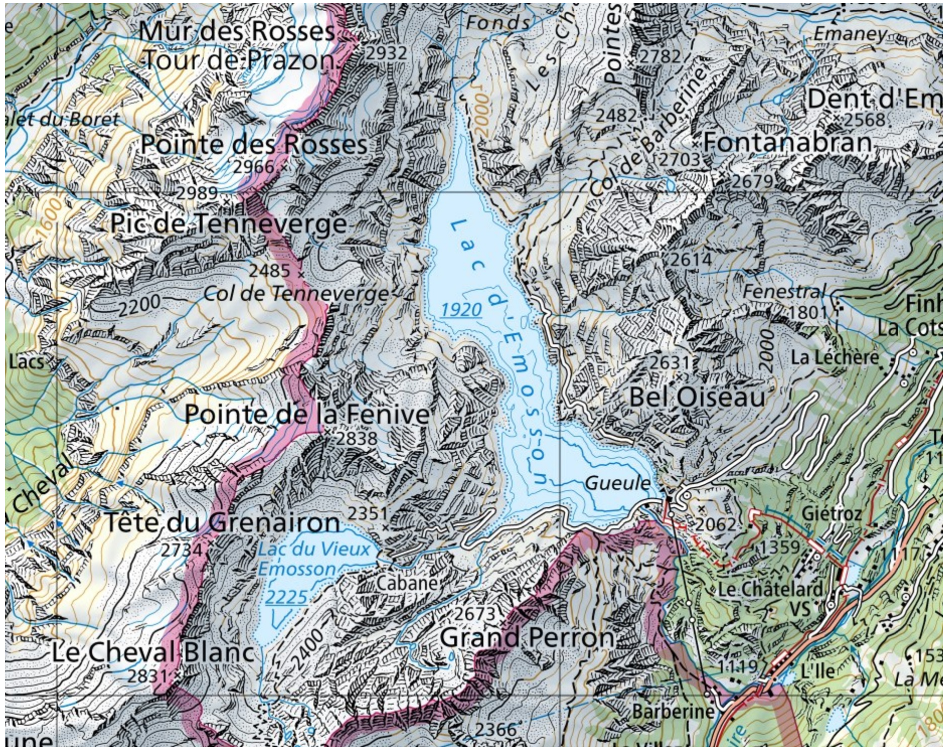

14
Stauanlage Muttsee 2474 m
Machine Cavern
KONECRANES
32 m
1
2
3
4
5
6
7
8
9
10
11
12
13
15
Limmernsee
12 Unterwasserdruckstollen
13 Ein- und Auslaufbauwerk
14 Hochwasserentlastung und Grundablass
15 Bauseilbahn 2 Ochsenstäfeli–Muttsee
axpo.ch
nant-de-drance.ch

Pump storage – Linthal

Nant-de-Drance

https://www.nant-de-drance.ch/en/





Appendix

Recall-Pump performance characteristics

- Overall efficiency $\eta = \dfrac{\text{power gained by the fluid}}{\text{shaft power driving the pump}} = \dfrac{P_f}{\dot{W}_{\text{shaft}}}$

  = ratio of power actually gained by the fluid to the shaft power supplied

- Hydraulic losses: Skin friction, flow separation, 3D and unsteady effects
  → Hydraulic efficiency η_h

- Mechanical losses: bearing and sealing losses
  → Mechanical efficiency η_m

- Volumetric losses: flow leakage components
  → Volumetric efficiency η_v

$$\eta = \eta_h \eta_m \eta_v$$