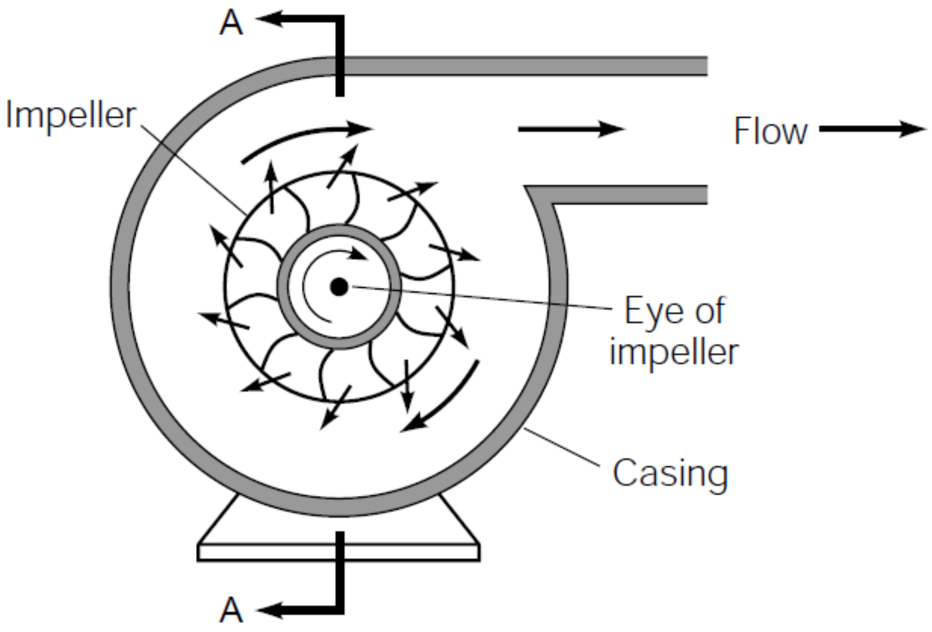
Water Resources Engineering and Management

(CIVIL-466, A.Y. 2024-2025)

5 ETCS, Master course



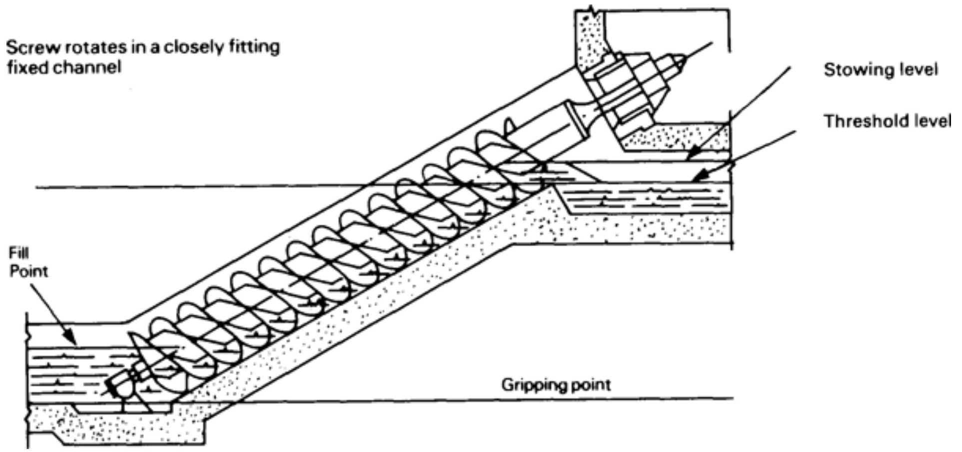
Lecture 3-3 Hydraulic machines: pumps and turbines

Prof. P. Perona
Platform of hydraulic constructions

Definition and type of pumps

Pumps are hydraulic machines that convert mechanical energy to fluid energy.
Two categories:

Positive displacement pumps deliver a fixed quantity of fluid with each revolution of the pump rotor, such as with a piston, a cylinder or a screw.

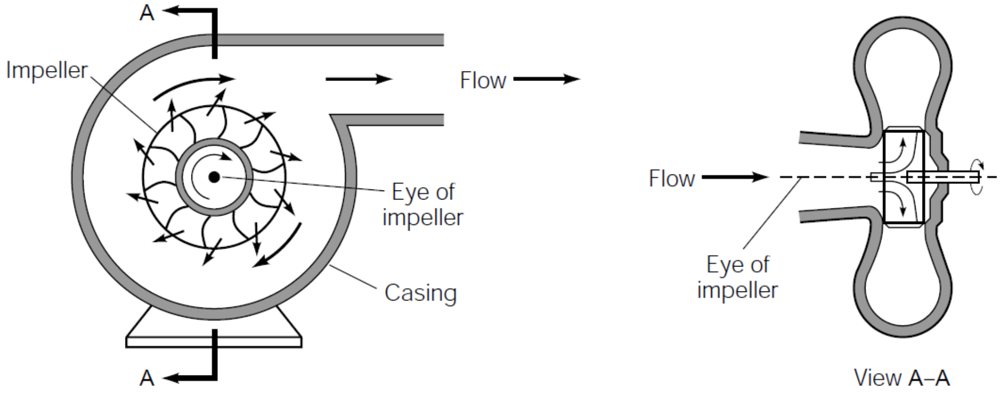


Screw pump usually employed in wastewater treatment plants because they can carry solid without clogging. They work at atmospheric pressure.

Rotodynamic or kinetic pumps add energy to the fluid by accelerating it through the action of a rotating impeller. Rotodynamic pumps are far more common in water distribution systems and will be our main focus.

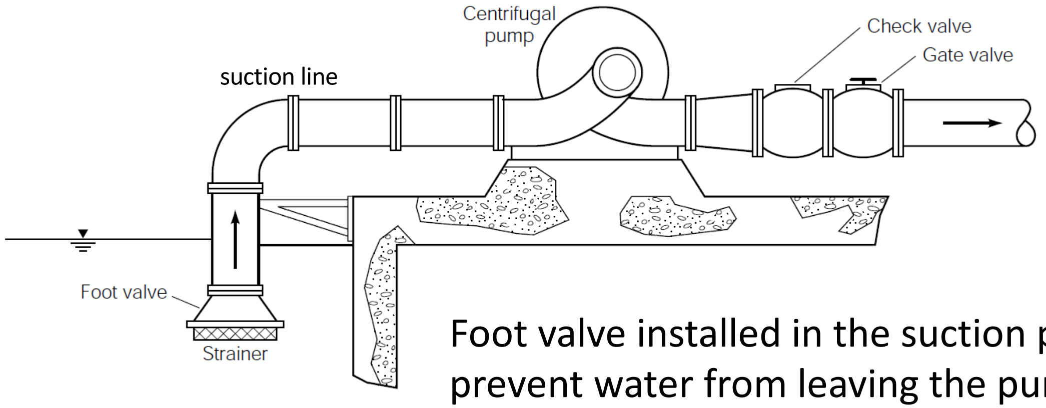
Courtesy of A. Rinaldo

radial or centrifugal pump



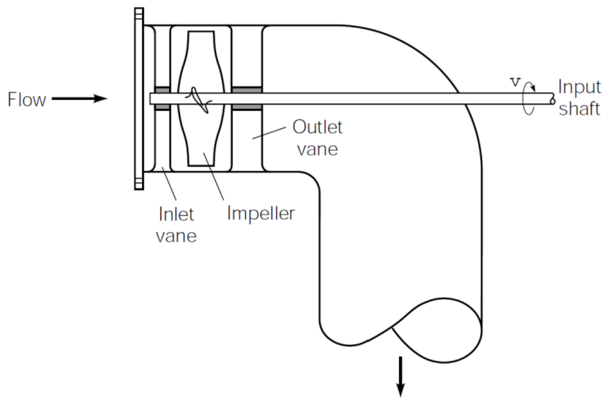
Flow enters the pump chamber along the axis of the impeller and is discharged radially by centrifugal action.

radial pump installation

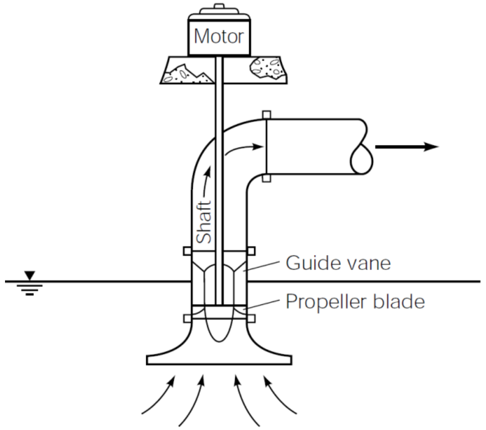


Foot valve installed in the suction pipe to prevent water from leaving the pump when it is stopped and a check valve in the discharge pipe to prevent backflow if there is a power failure.

axial pump

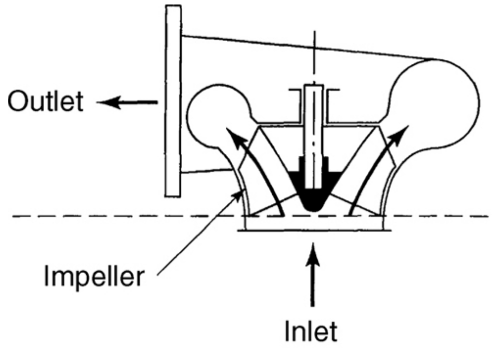


axial pump installation



Flow enters and leaves the pump chamber along the axis of the impeller.

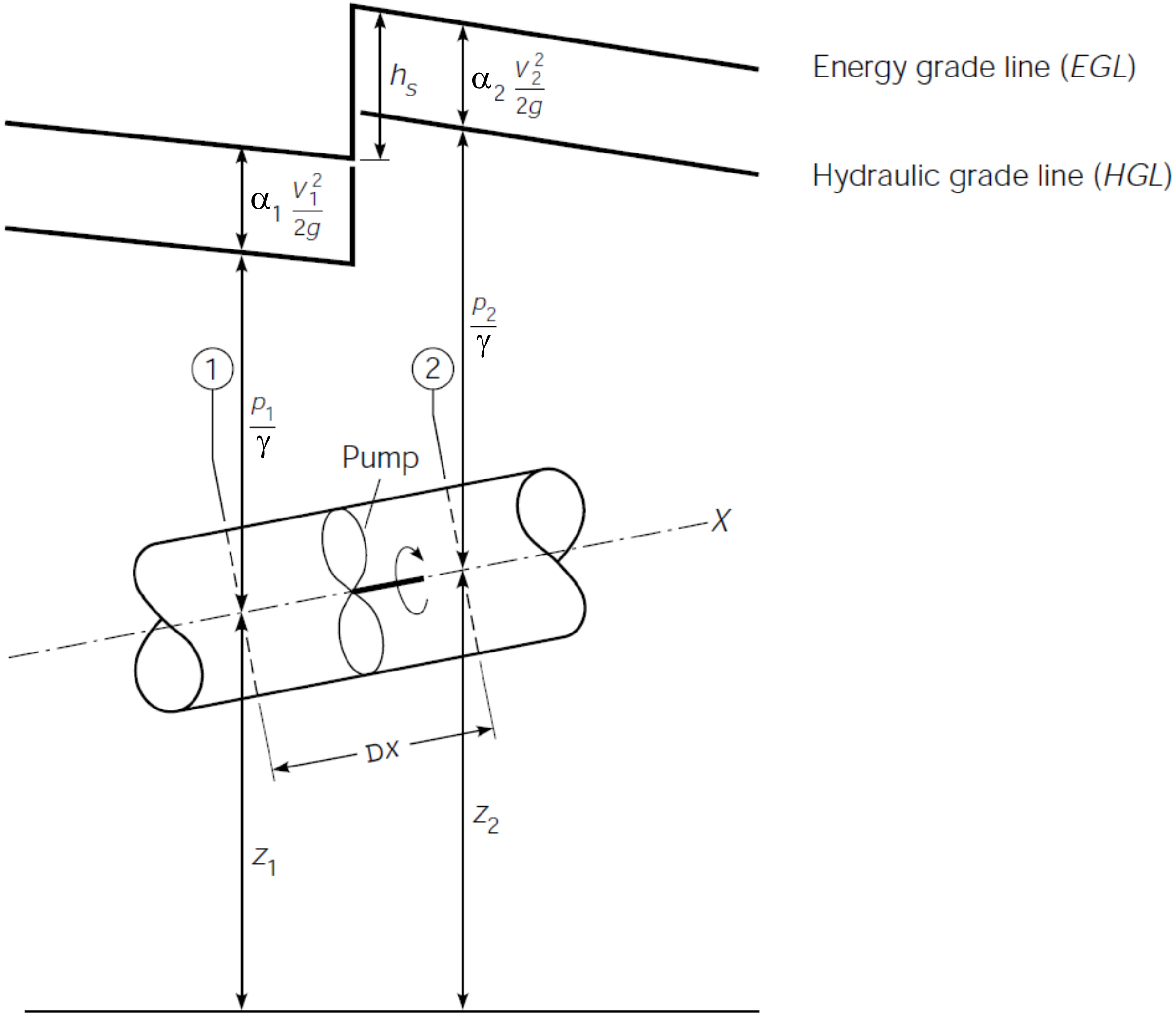
mixed-flow pump



Flow has both radial and axial components.

Courtesy of A. Rinaldo

Functioning principle and energy lines



Example of energy grade line EGL and hydraulic grade line HGL with a pump

h_s shaf energy per unit of weight delivered by the pump to the water.

Power [W] delivered to the fluid $\gamma\ Q\ h_s$

Pump efficiency h

Power demand [W]:

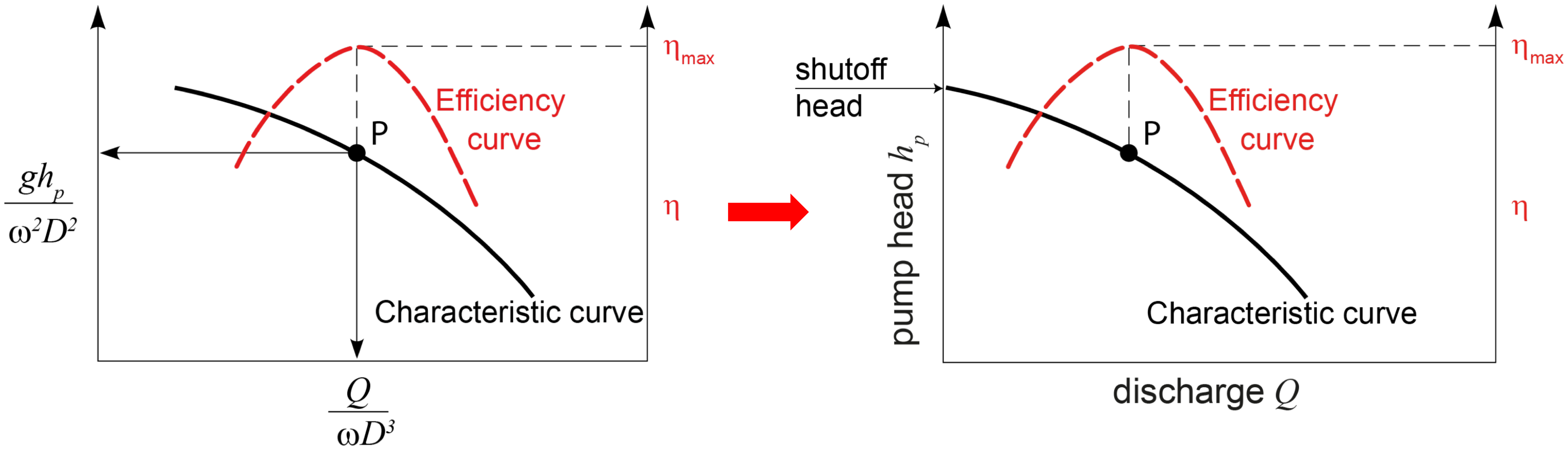
$P = \gamma\ Q\ h_s / \eta$

Courtesy of A. Rinaldo

Characteristic and efficiency curves

characteristic curve: total head h_p versus discharge Q that the pump can supply

efficiency curve: efficiency η versus discharge $$\eta = \frac{\text{power delivered to the fluid}}{\text{power supplied to the shaft}}$$

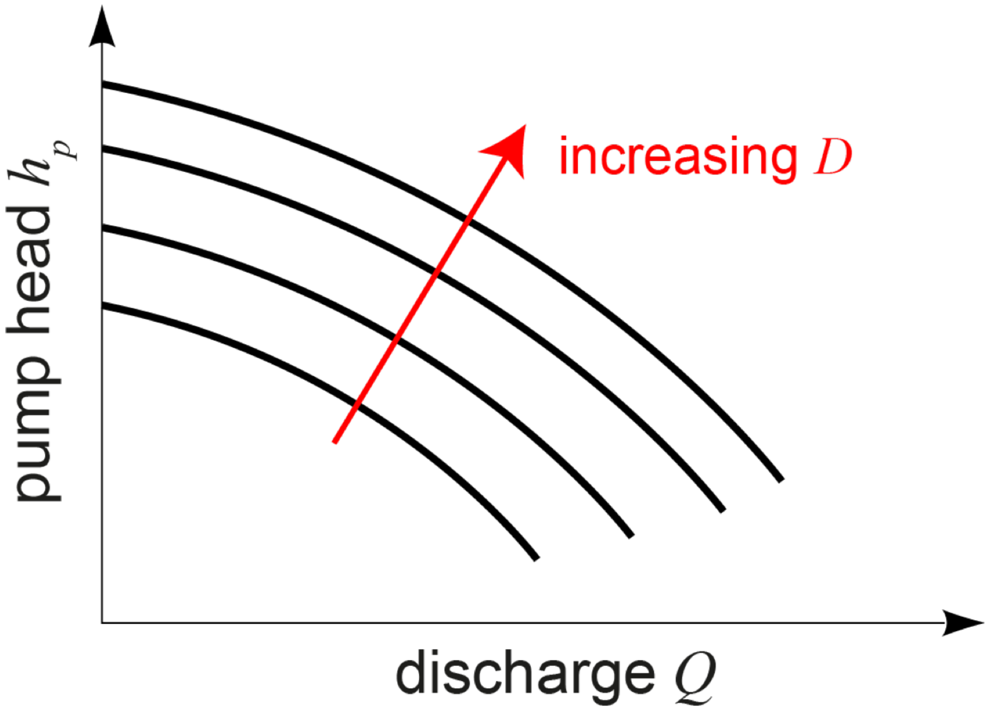


shutoff head: head provided by the pump when the discharge is null

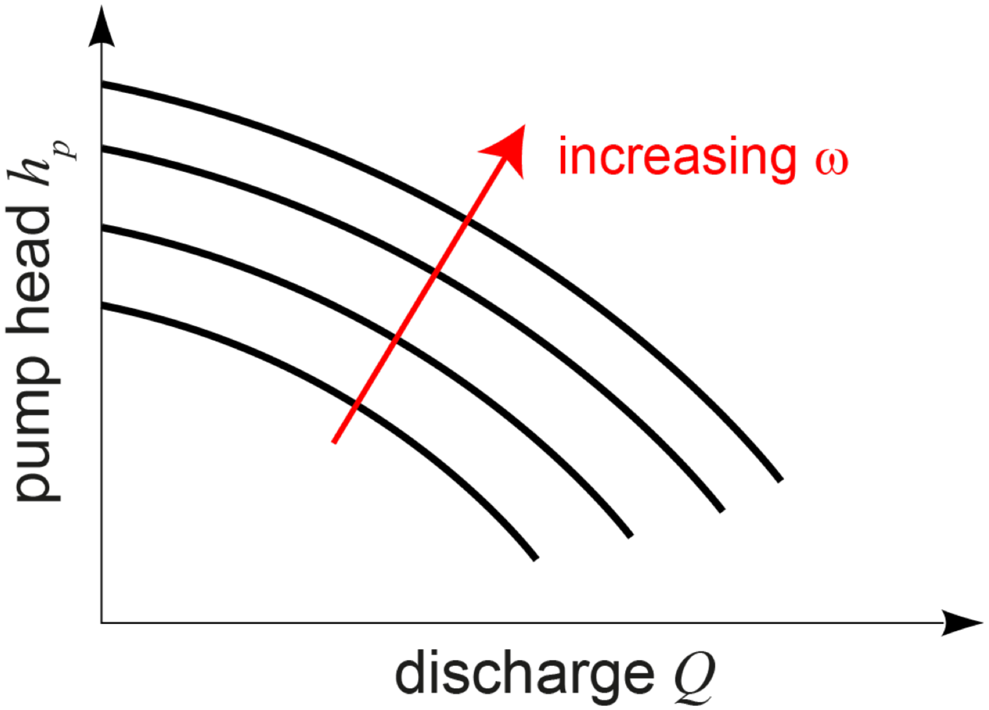
Courtesy of A. Rinaldo

Characteristic curves: effects of D and ω

different diameters D for the same homologous series



different rotation speed ω for the same pump



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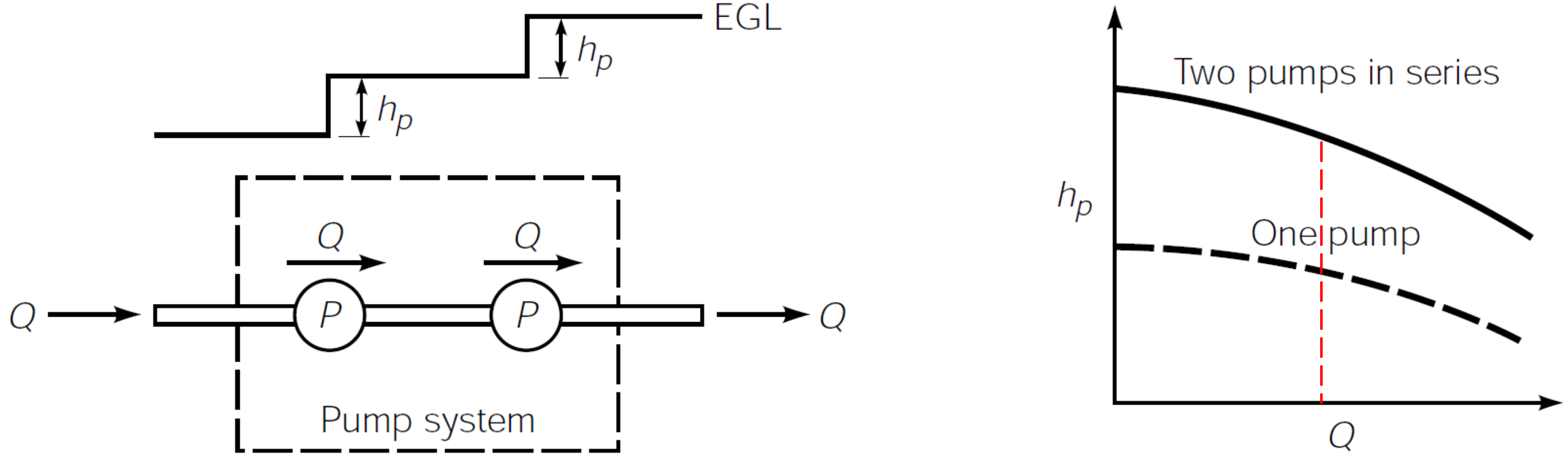
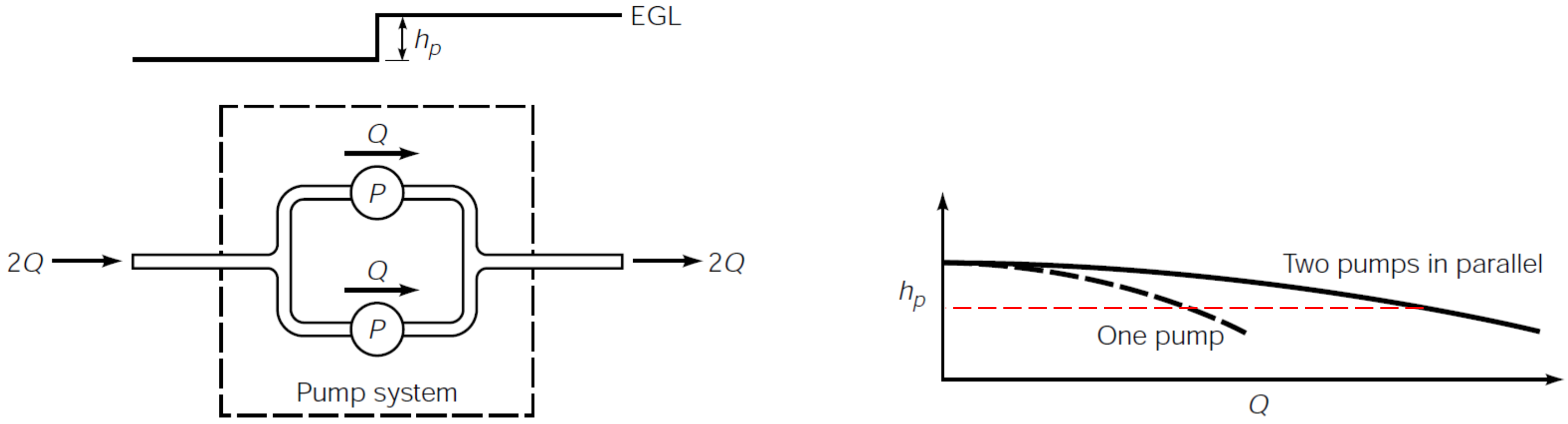
Characteristic curves: parallel or series configuration



two pumps in series: the discharge is the same, the head is summed



two pumps in parallel: the head is the same, the discharge is summed

Courtesy of A. Rinaldo

System curve and functioning (operating) point

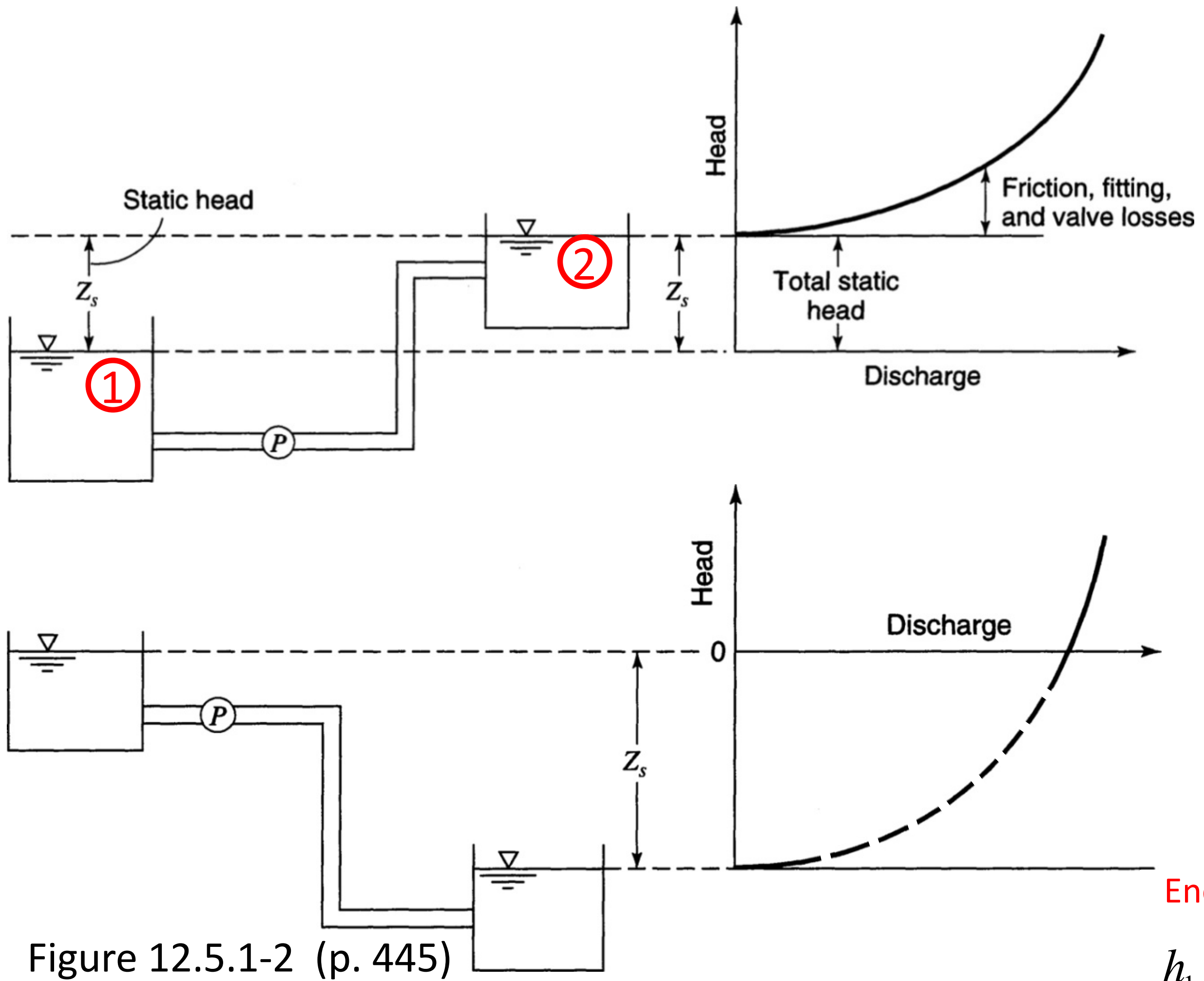


Figure 12.5.1-2 (p. 445)

system curve: relationship between the head that a pump should provide in order to deliver a certain discharge through a pipeline system. It depends only on the characteristics of the pipeline system

head losses computed for different pipes, fittings and valves composing the pipeline system. Ai cross sectional areas of the pipes

Energy conservation

$$h_1 = h_2 + h_L - h_p \rightarrow h_p = z_2 - z_1 + h_L$$

$$h_p = z_s + h_L = z_s + kQ^2 = z_s + Q^2\left[\sum_i \frac{f_i L_i}{2gD_i A_i^2} + \sum_i \frac{K_i}{2gA_i^2}\right]$$

Functioning (operating) point

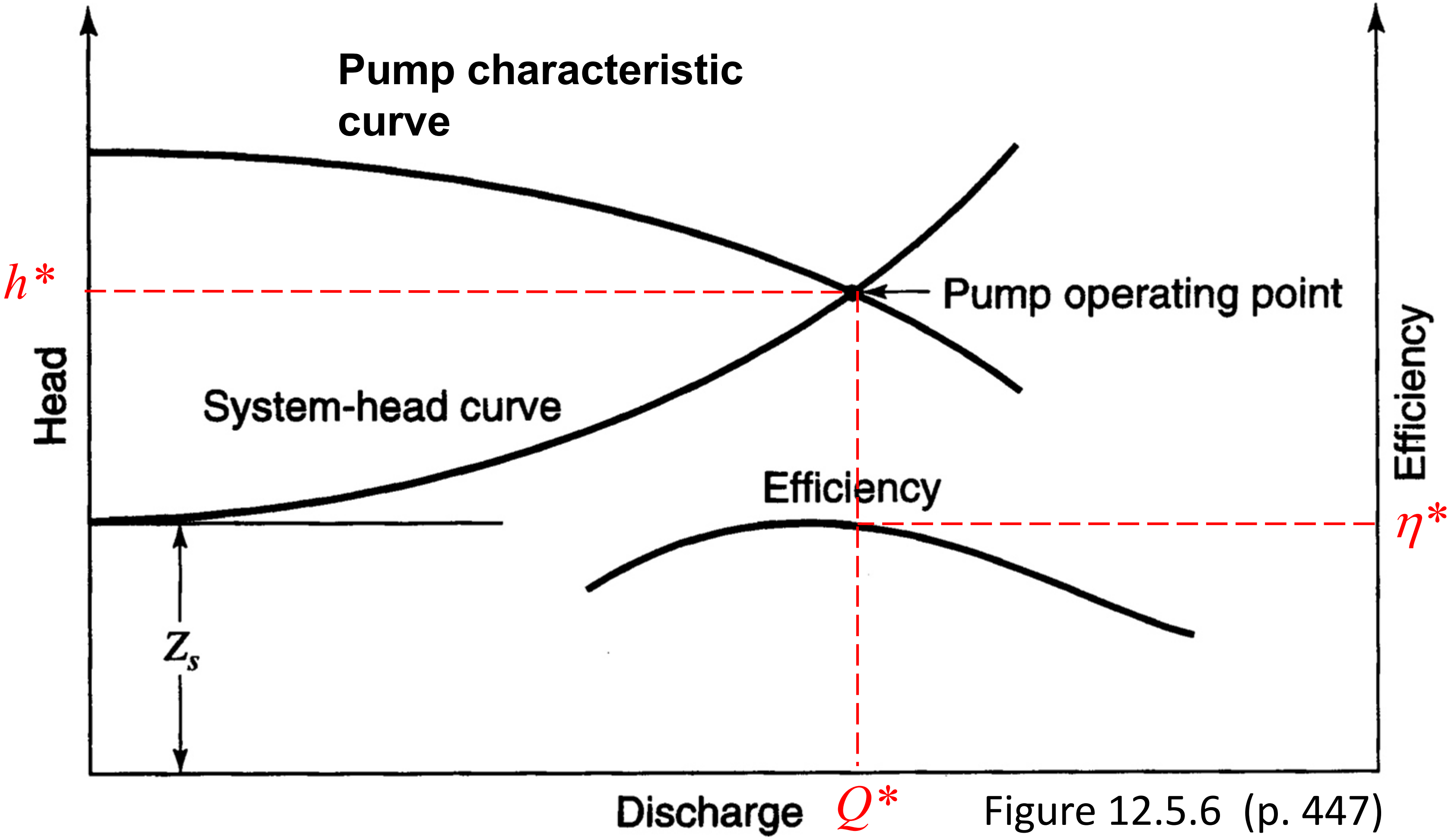
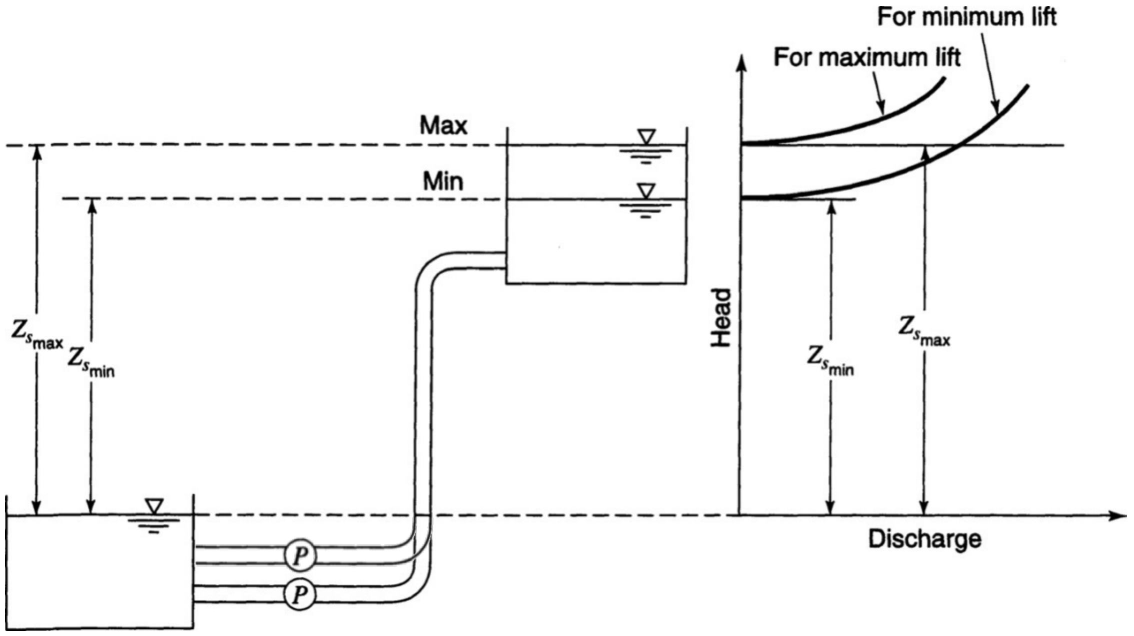


Figure 12.5.6 (p. 447)

Equilibrium is reached at the operating point *, i.e., the discharge at which the head provided by the pump meets the head needed by the pipeline system.

Courtesy of A. Rinaldo

Control of operating point



control through multiple pumps
system with two pumps in parallel
and a varying static lift

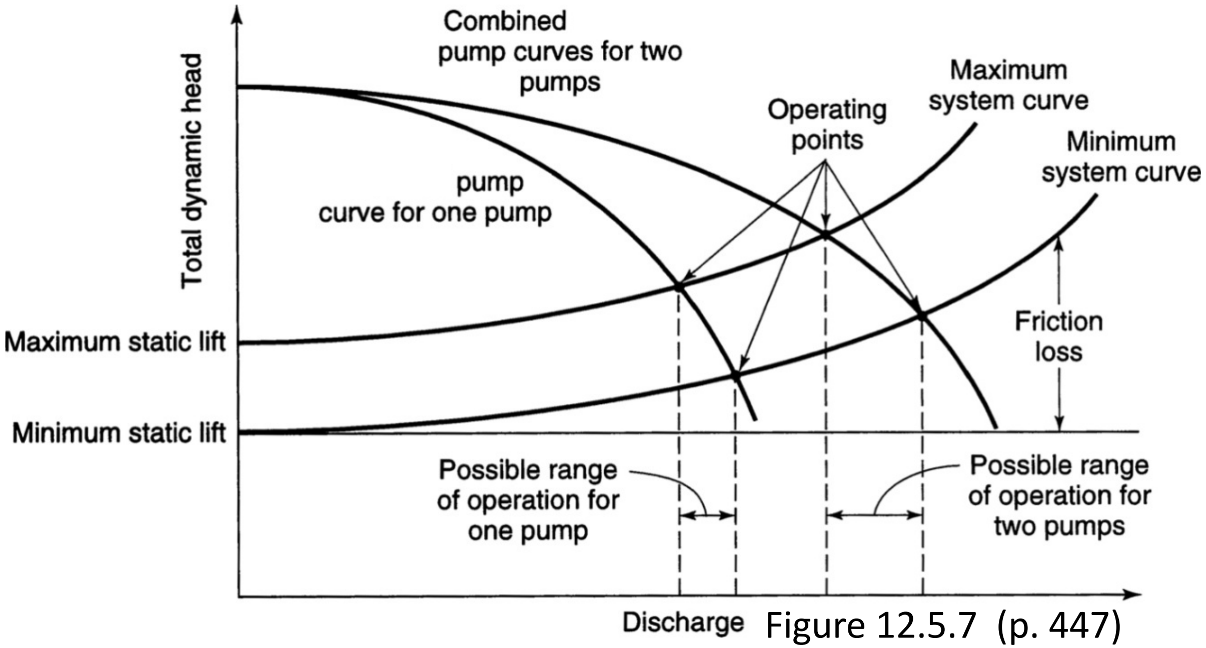


Figure 12.5.7 (p. 447)

Courtesy of A. Rinaldo

Control of operating point

control through multiple pumps

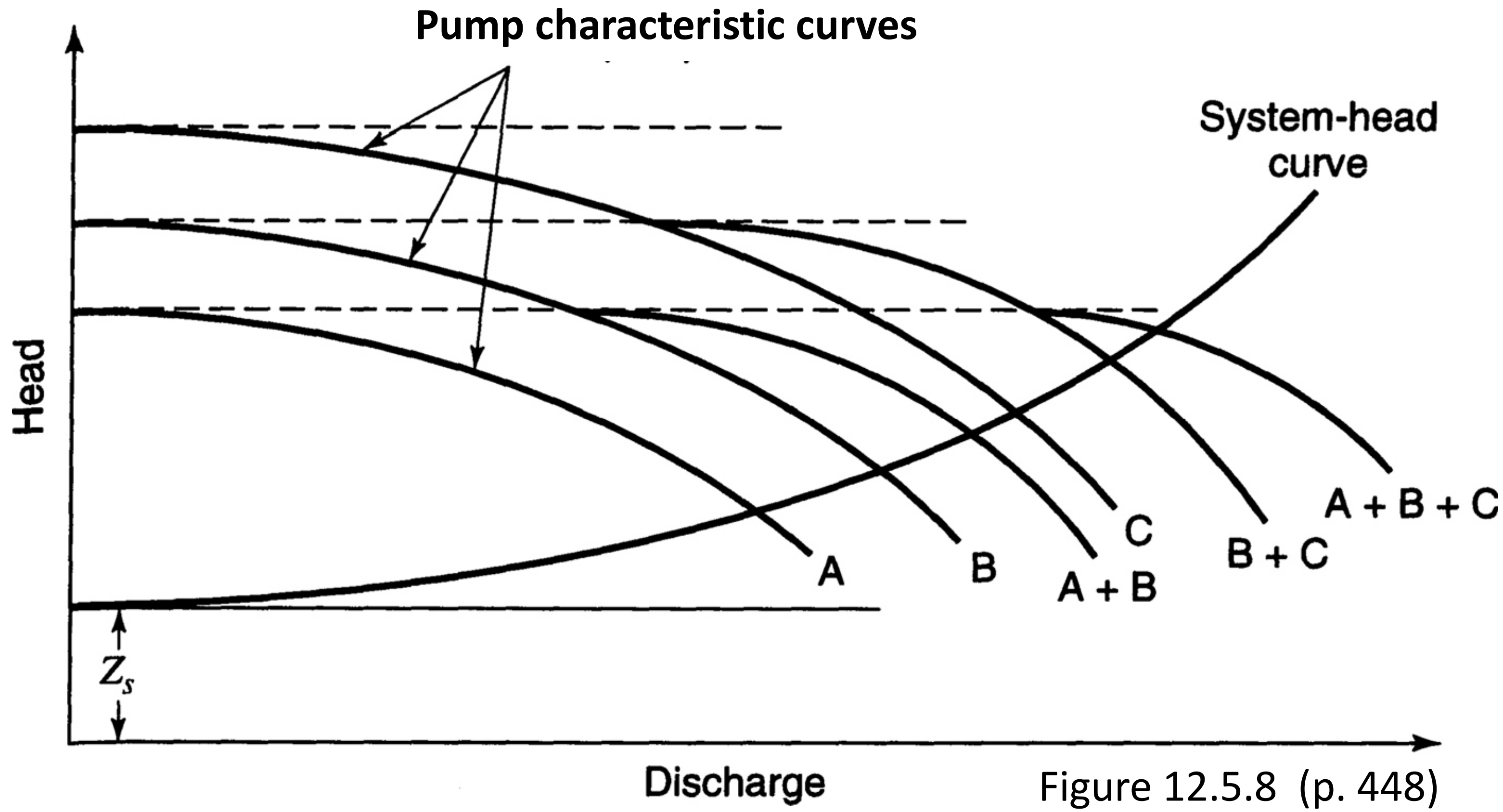


Figure 12.5.8 (p. 448)

System with three pumps of different sizes operating in parallel

Courtesy of A. Rinaldo

Control of operating point

control through variable speed

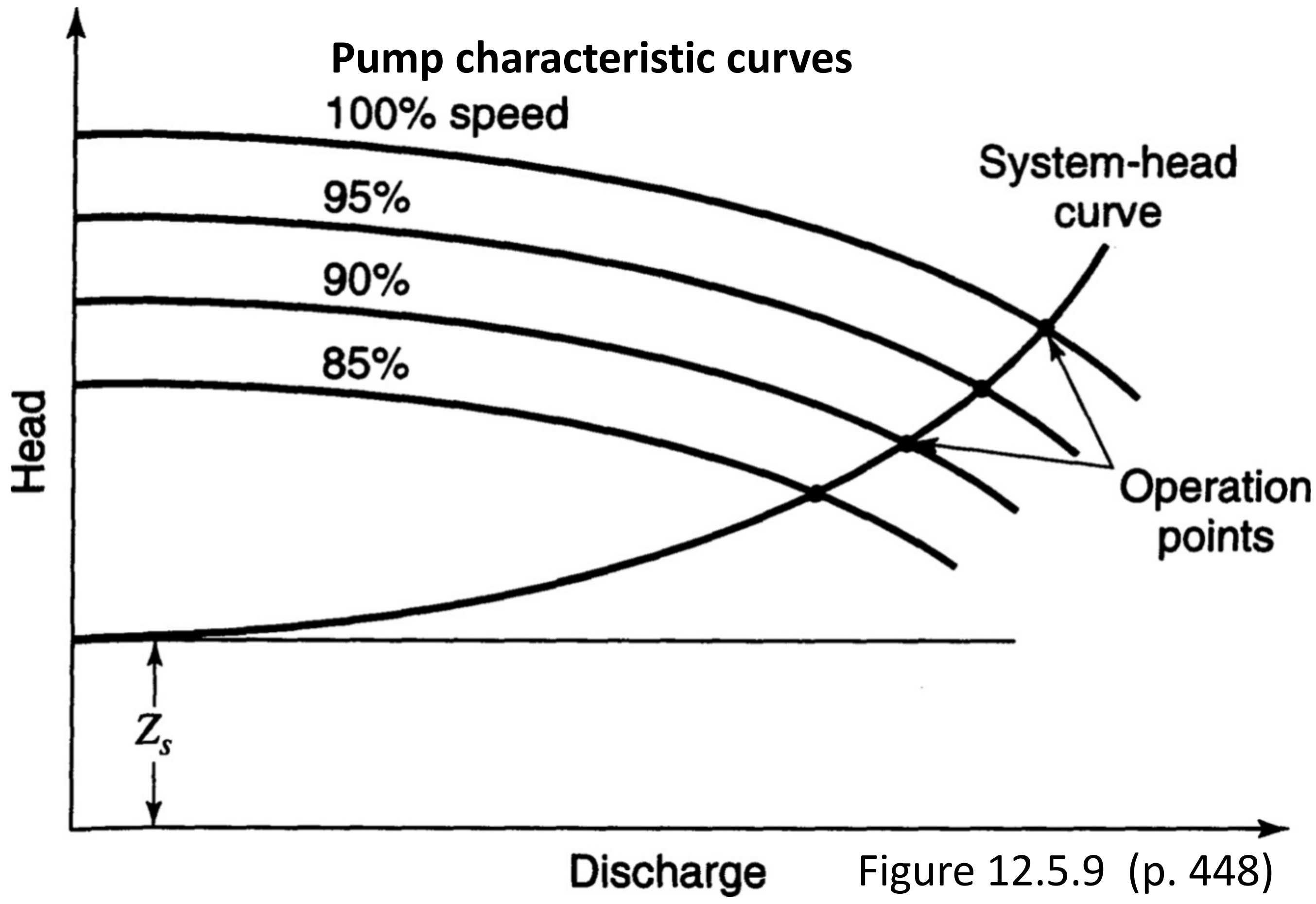


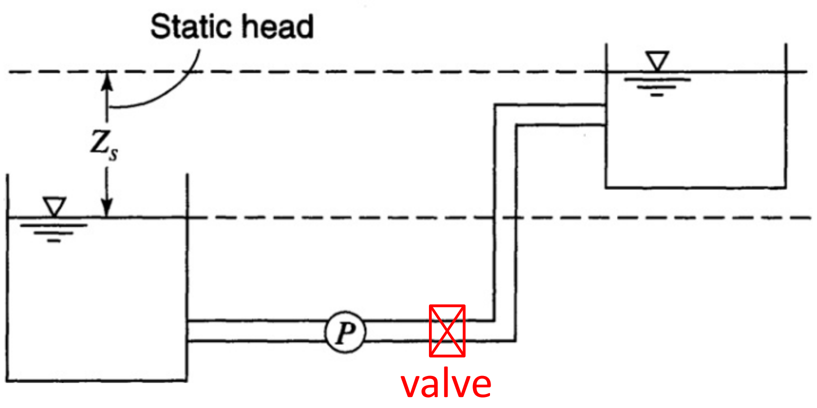
Figure 12.5.9 (p. 448)

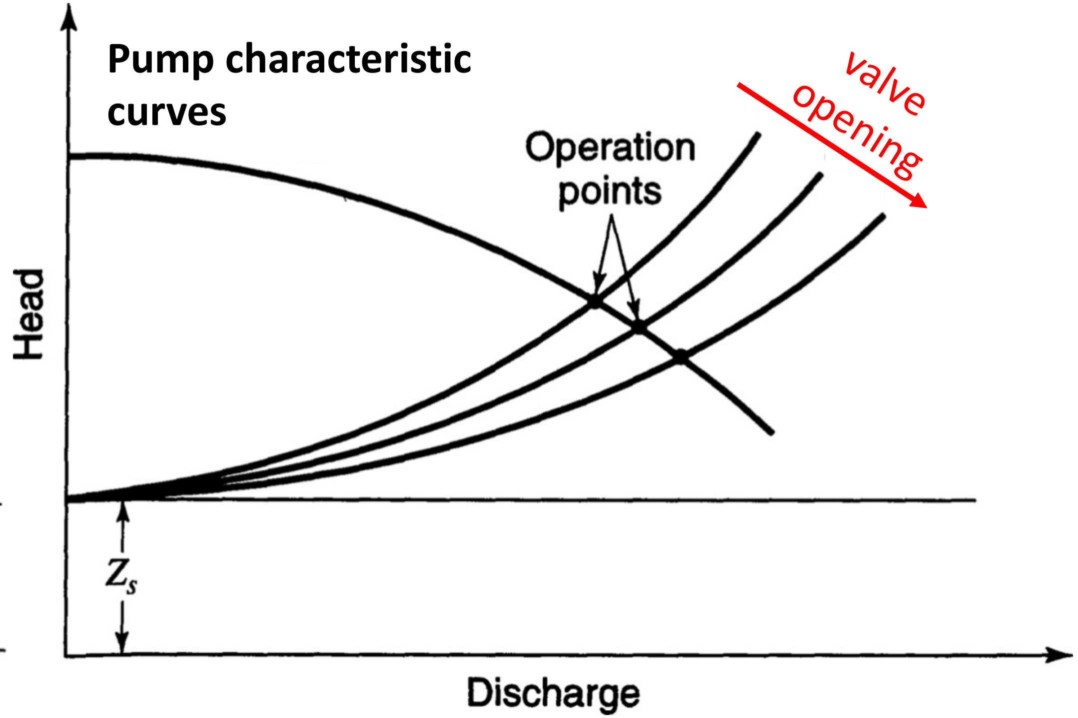
System with a single pump operated at variable speed

Courtesy of A. Rinaldo

Control of operating point

control through valve throttle





System with a single pump and a valve. By closing the valve the head loss increases

Courtesy of A. Rinaldo

Limits on pump location

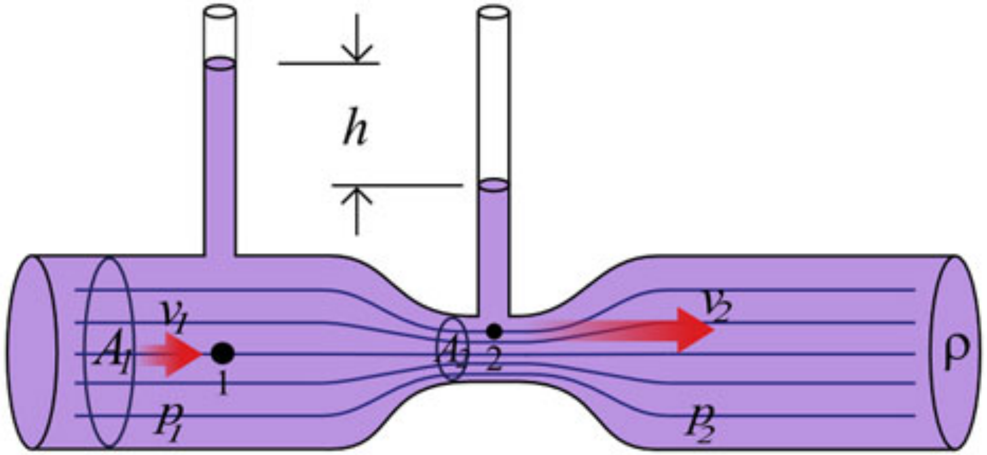
saturation vapor pressure of a fluid is defined as the partial pressure of the gaseous phase of the fluid in equilibrium with the fluid phase (no net exchange of mass).

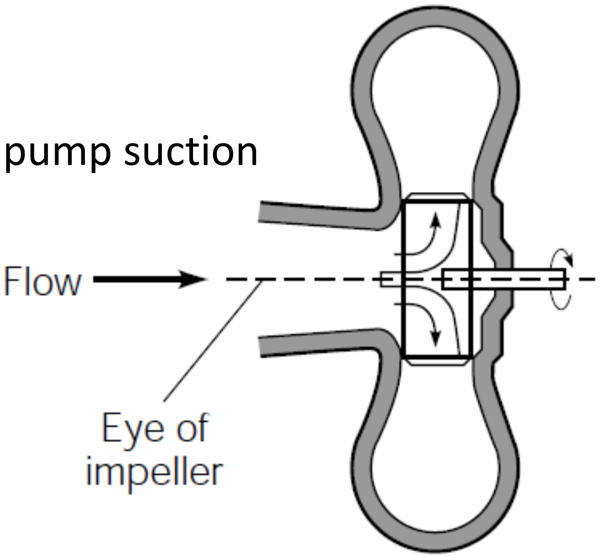
vapor pressure < saturation vapor pressure → mass flux from the fluid to the vapor phase and viceversa

Whenever the temperature of the water is such that the saturation vapor pressure equals the pressure in the water body, vapor cavities are formed to maintain equilibrium between the liquid and the vapor phase. This process is called cavitation and the water is said to be boiling.

This boiling phenomenon can be achieved by reducing the pressure in the water body so that the water pressure becomes equal to the saturation vapor pressure.

Example: Venturi tube, pressure reduction due to flow acceleration (energy conservation)





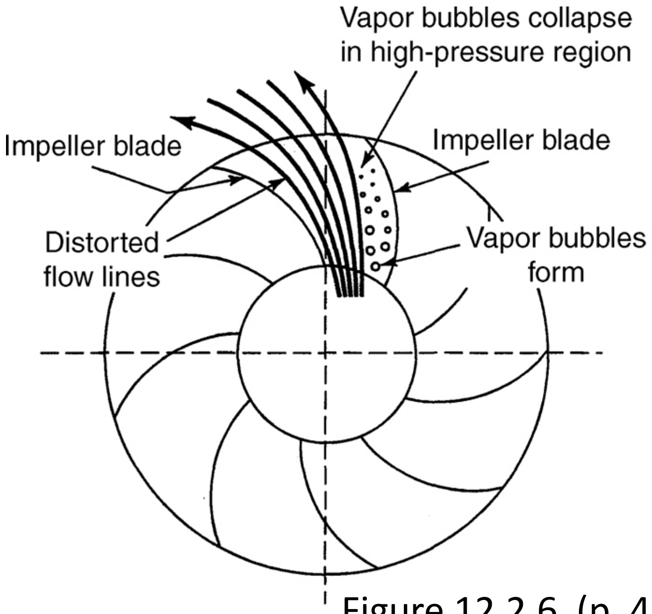
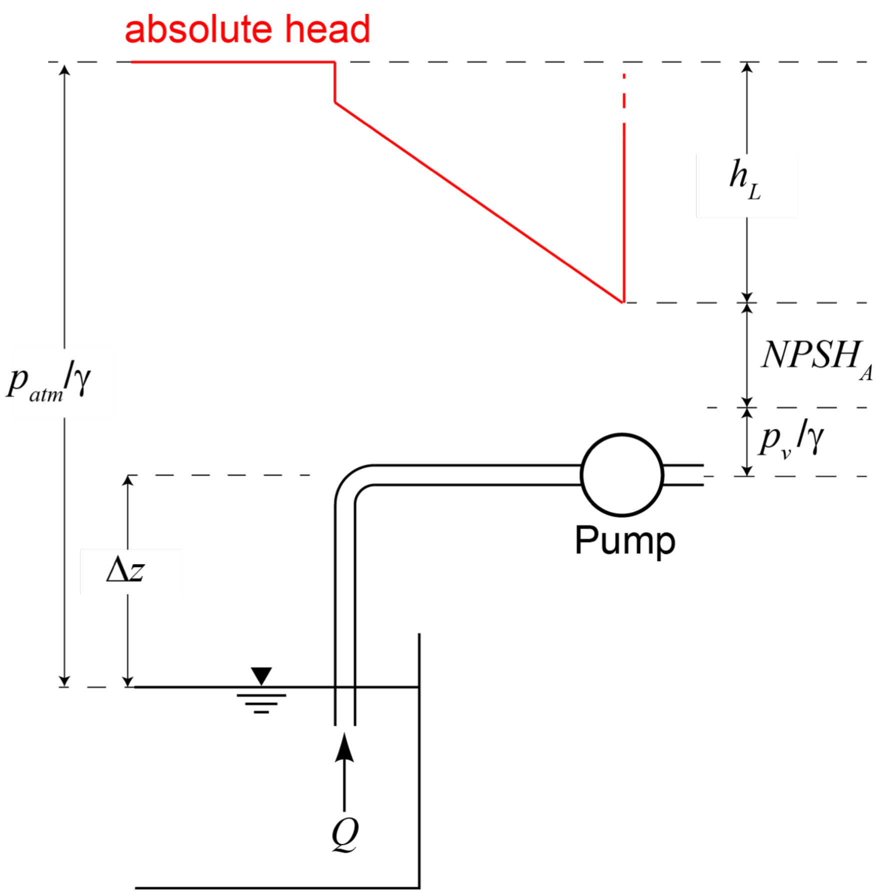


Figure 12.2.6 (p. 427)

from the suction of the pump to the first part of the impeller the water accelerates and thus the pressure drops (for energy conservation). This reduction can cause, depending on temperature and absolute pressure, cavitation. Proceeding toward the external part of the impeller, the water decelerates and thus the pressure increases causing the implosion of the cavities that can cause vibration and damage the machinery

Courtesy of A. Rinaldo



Net Positive Suction Head ($NPSH$) difference between the absolute head (i.e. when absolute pressure and not gage pressure is considered) of the fluid at the suction side of a pump and the absolute head at which cavitation occur.

$$NPSH = \left(z_s + \frac{p_s}{\gamma} + \frac{v_s^2}{2g} \right) - \left(z_s + \frac{p_v}{\gamma} \right)$$

$$= \frac{p_s}{\gamma} - \frac{p_v}{\gamma} + \frac{v_s^2}{2g}$$

where p_s, V_s and z_s are the absolute pressure, velocity and elevation of the fluid at the suction of the pump and p_v is the saturation vapor pressure of water at that temperature

$NPSH$ available ($NPSH_A$) at the suction side of the pump

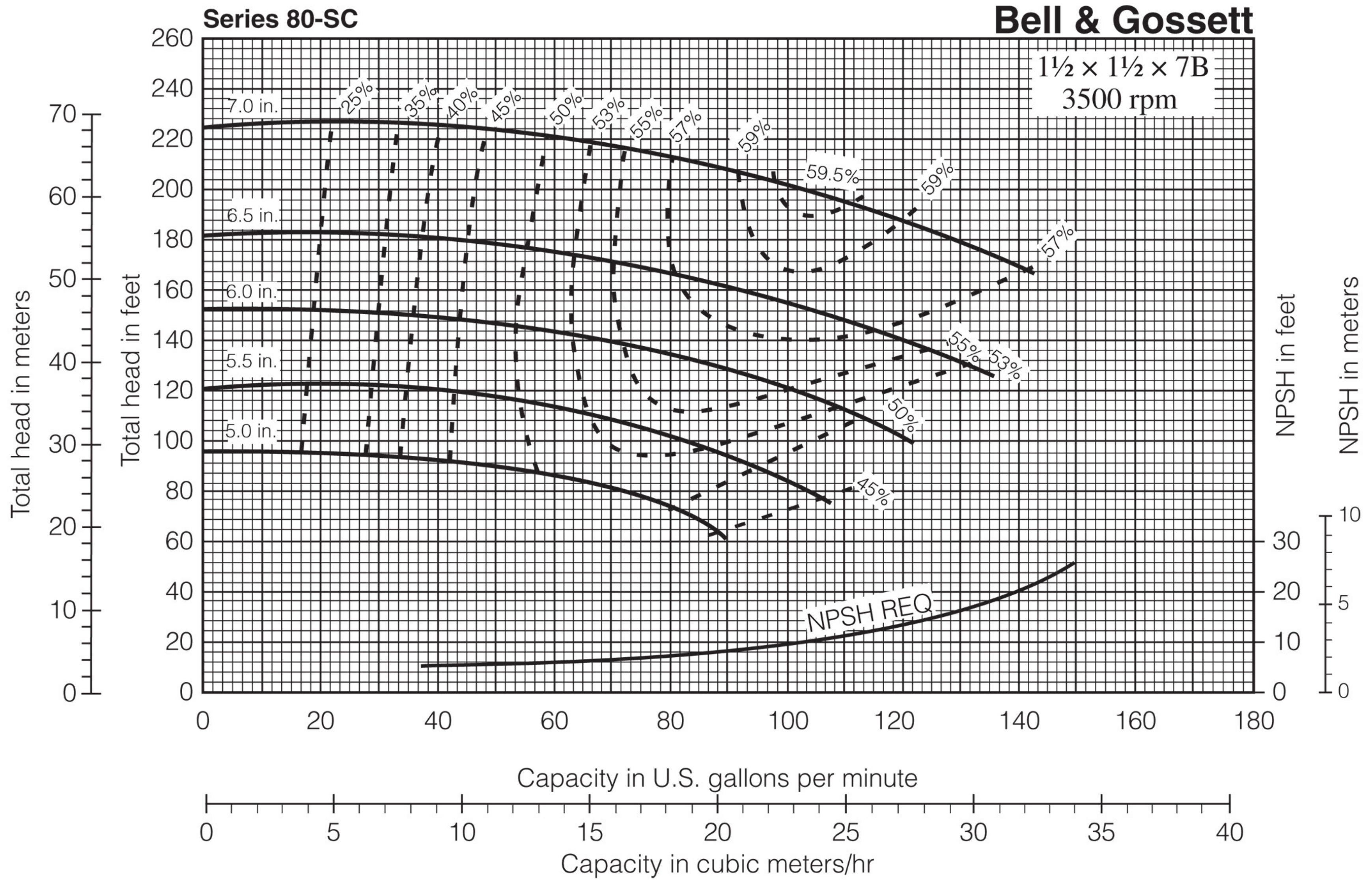
$$NPSH_A = \frac{p_{atm}}{\gamma} - \Delta z - h_L - \frac{p_v}{\gamma}$$

where h_L are the head losses from the entrance to the pump.

To avoid cavitation, $NPSH_A$ must be greater than the required $NPSH$ ($NPSH_R$) which is provided by the pump manufacturer (depending on the type of pump and operating conditions)

Typical values: $p_{atm}/\gamma \approx$ 10 m, $p_v/\gamma \approx$ 0.2 m at 20 C. Therefore $\Delta z < 10$ m

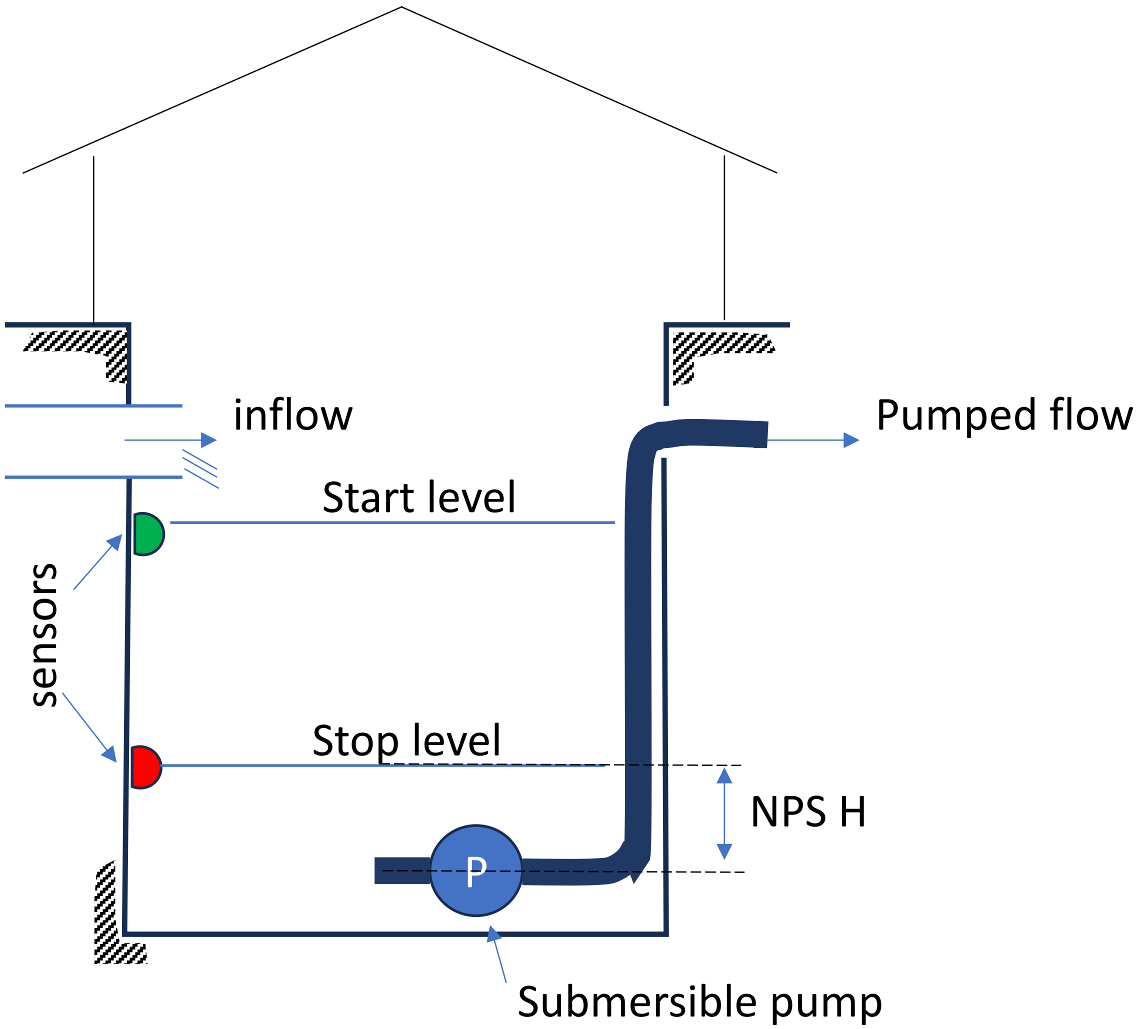
Courtesy of A. Rinaldo



Example of a pump chart provided by the manufacturer. Different solid lines refer to different diameters. Dashed lines indicate isolines at equal efficiency.

Courtesy of A. Rinaldo

Start-stop problems

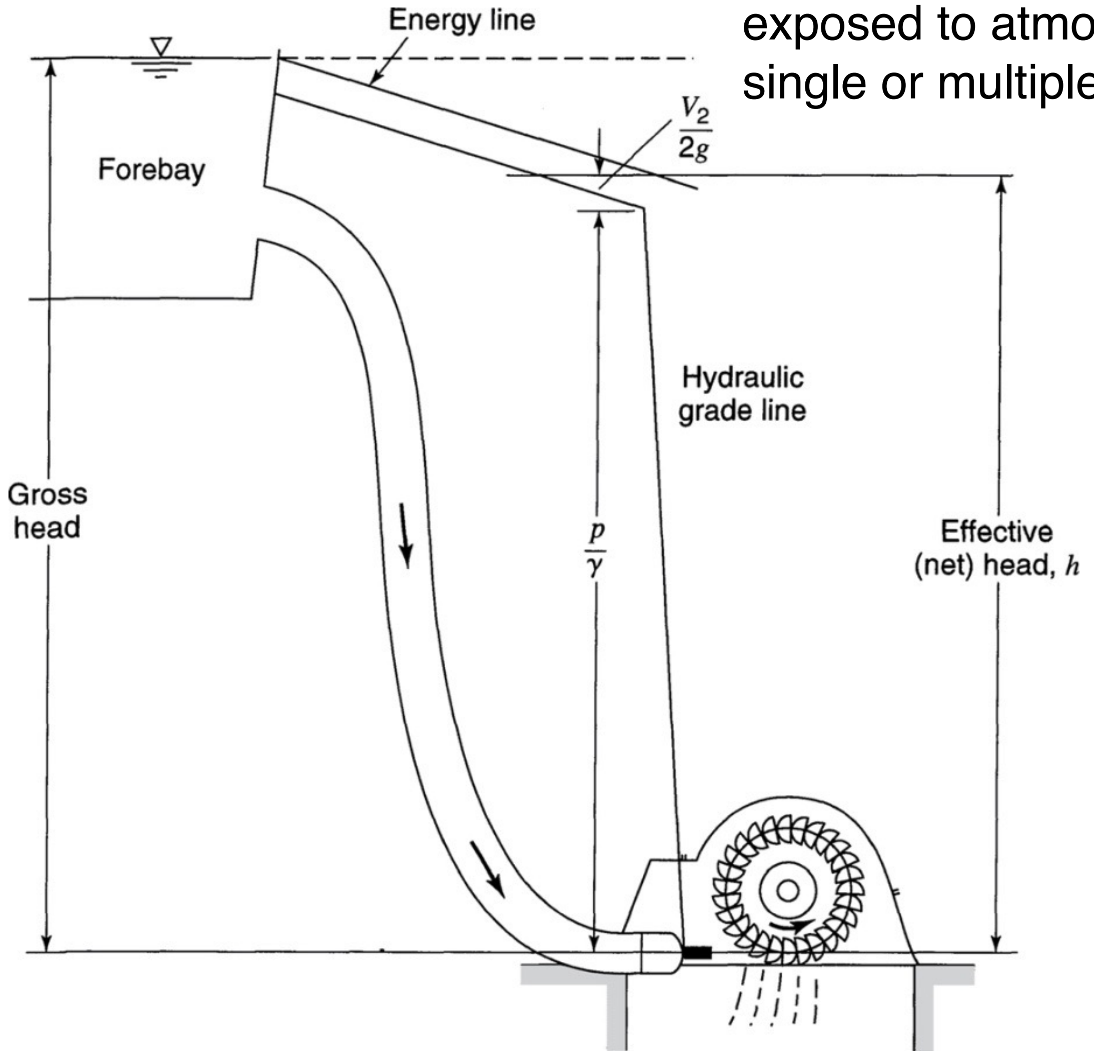


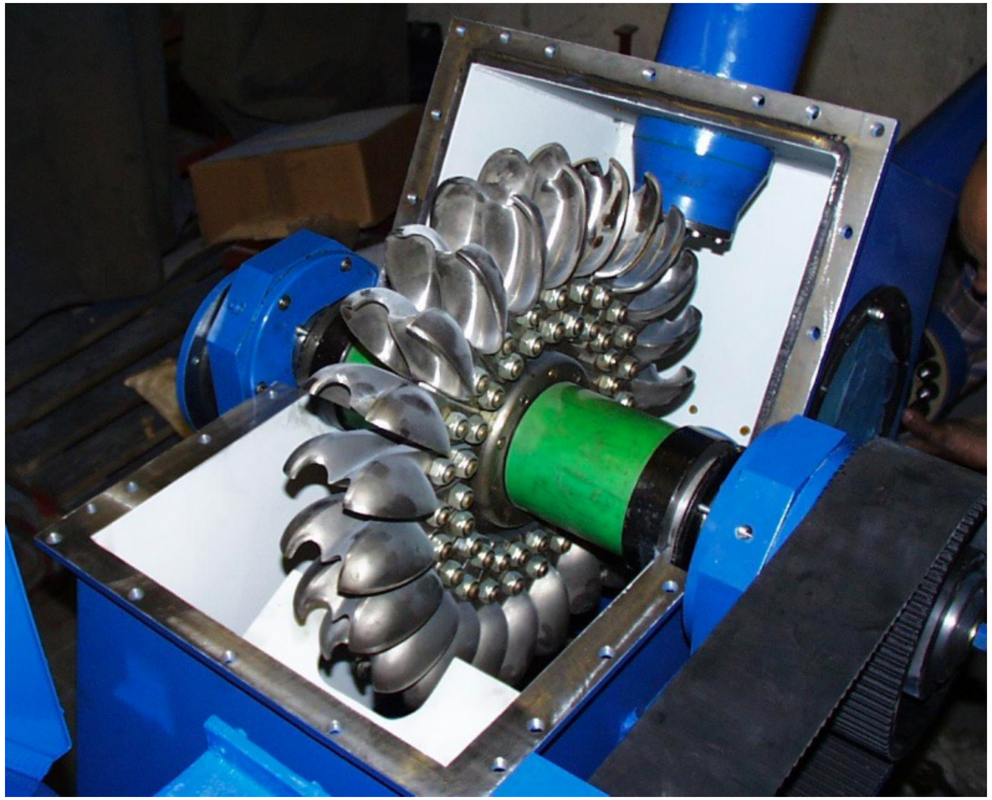
- NPSH (Net Pumping Suction Head)
  - Head required over pump inlet to prevent cavitation (not shown on this diagram)

Turbines: definitions and types

Impulse Turbine (Pelton)

A free jet of water impinges on a rotating runner which is exposed to atmospheric pressure. The turbine can have single or multiple jets.





Courtesy of A. Rinaldo

Hydraulic of a Pelton turbine

Hydraulic of Pelton turbine

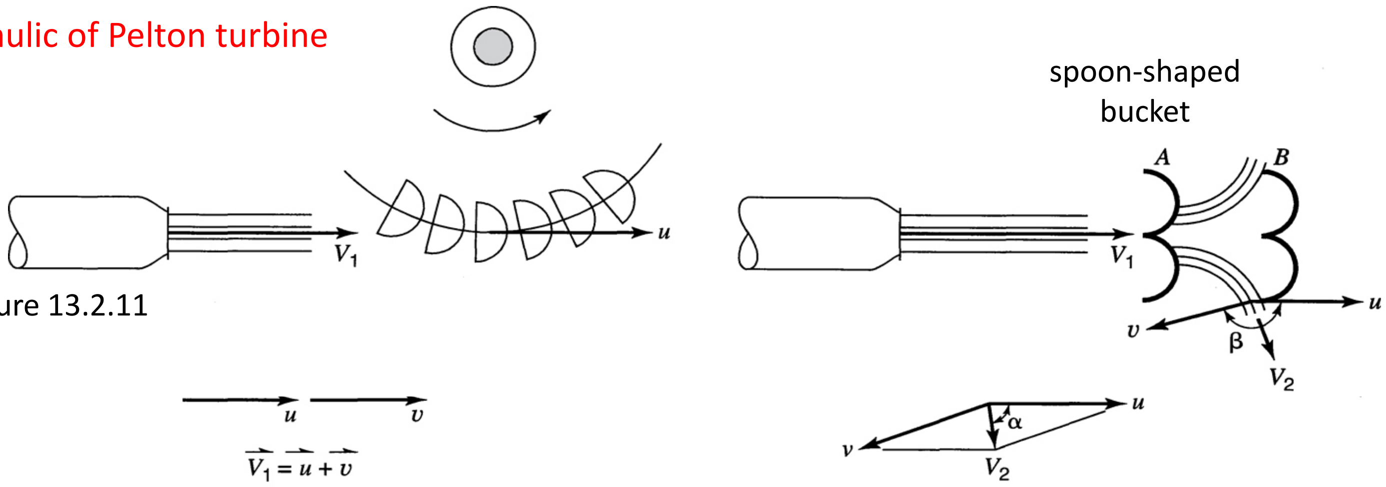


figure 13.2.11

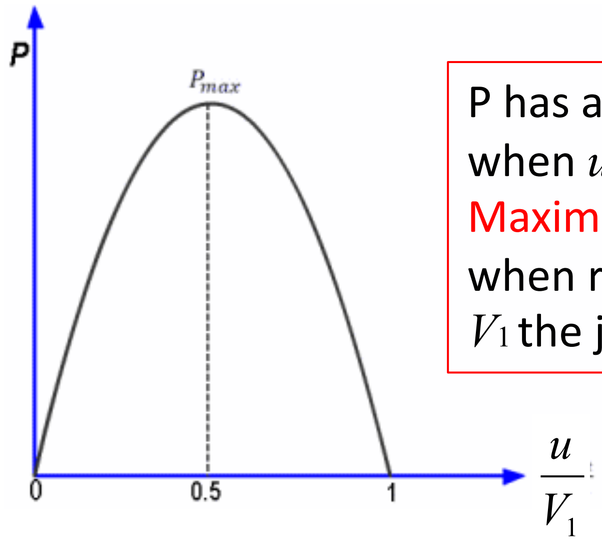
V_1: impinging jet velocity, V_2: exit jet velocity, u: runner velocity, v: velocity relative to the runner The tangential force F exerted by the jet on the runner is:

$$F = m\frac{\Delta V_t}{\Delta t} = \frac{m}{\Delta t}(V_1 - V_2\cos\alpha) = \rho Q(u + v - (u + v\cos\beta))$$

$$= \rho Q v(1-\cos\beta) = \rho Q(V_1 - u)(1-\cos\beta)$$

where V_t is the tangential component of the velocity and Q is the discharge. The power P transmitted to the runner:

$$P = Fu = \rho Q(V_1 - u)(1-\cos\beta)u$$



P has a maximum (dP/du=0) when $u=V_1/2$.
Maximum hydraulic efficiency when runner velocity is half of V_1 the jet velocity

Courtesy of A. Rinaldo

Reactive turbines (Francis and Kaplan type)

The flow takes place in a close chamber under pressure. Because the casing cannot withstand extremely high pressure, the head at which they can operate is typically lower than that of impulse turbines.

Francis turbine:
radial flow

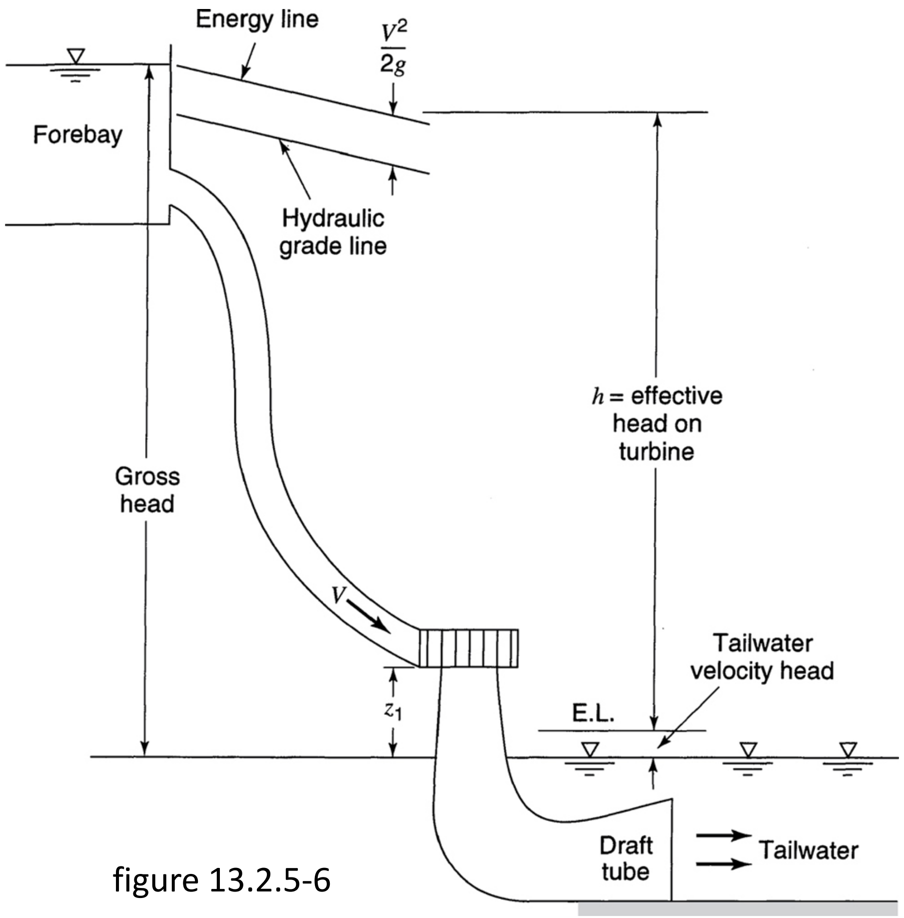
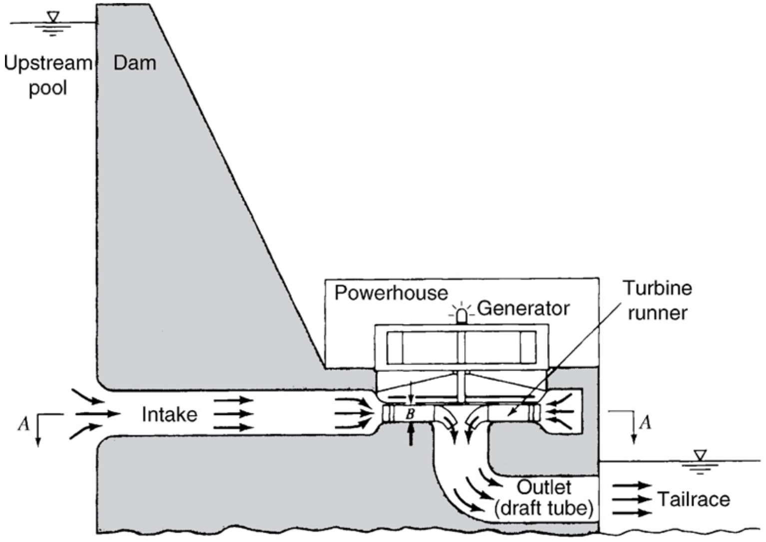
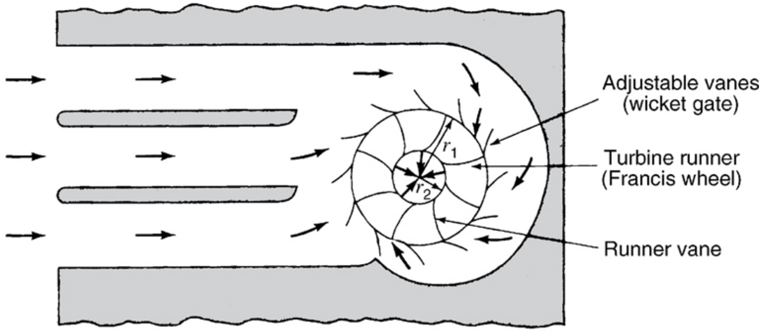


figure 13.2.5-6



(a)

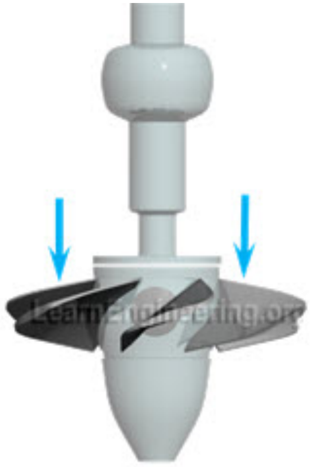


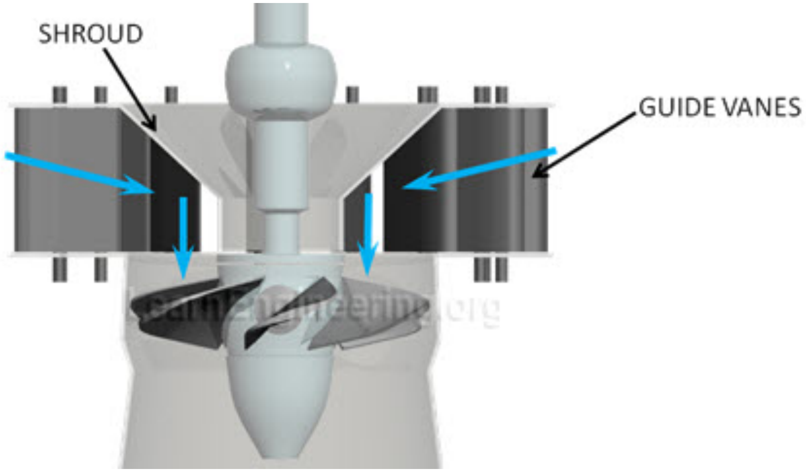
(b)

Courtesy of A. Rinaldo

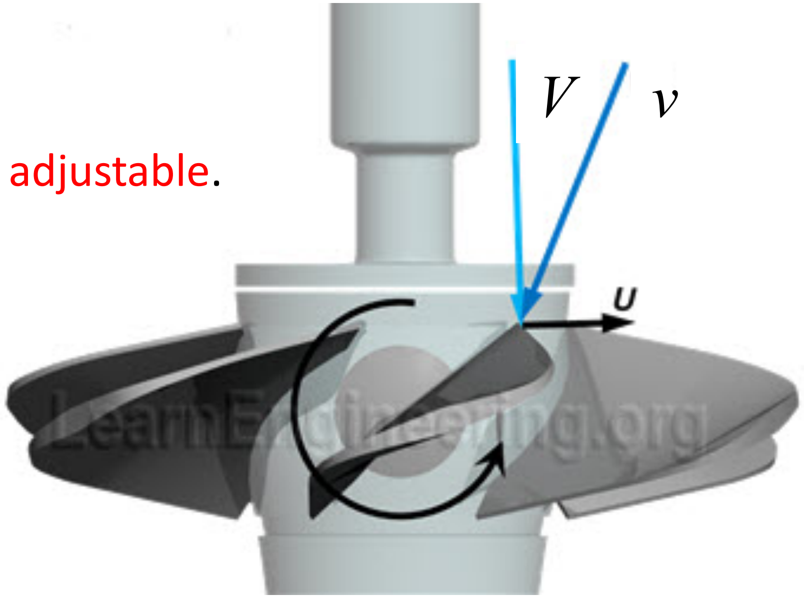
Reactive turbine. Kaplan. Axial flow. Turbine are designed to operate under a wide range of conditions. Position of guide vanes is used to control water flow rate.

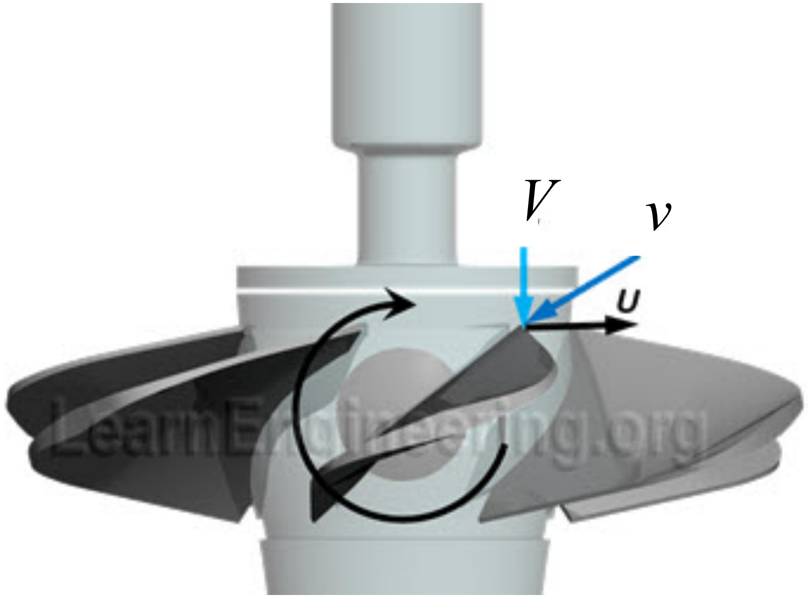
PLATEFORME DE CONSTRUCTIONS HYDRAULIQUES





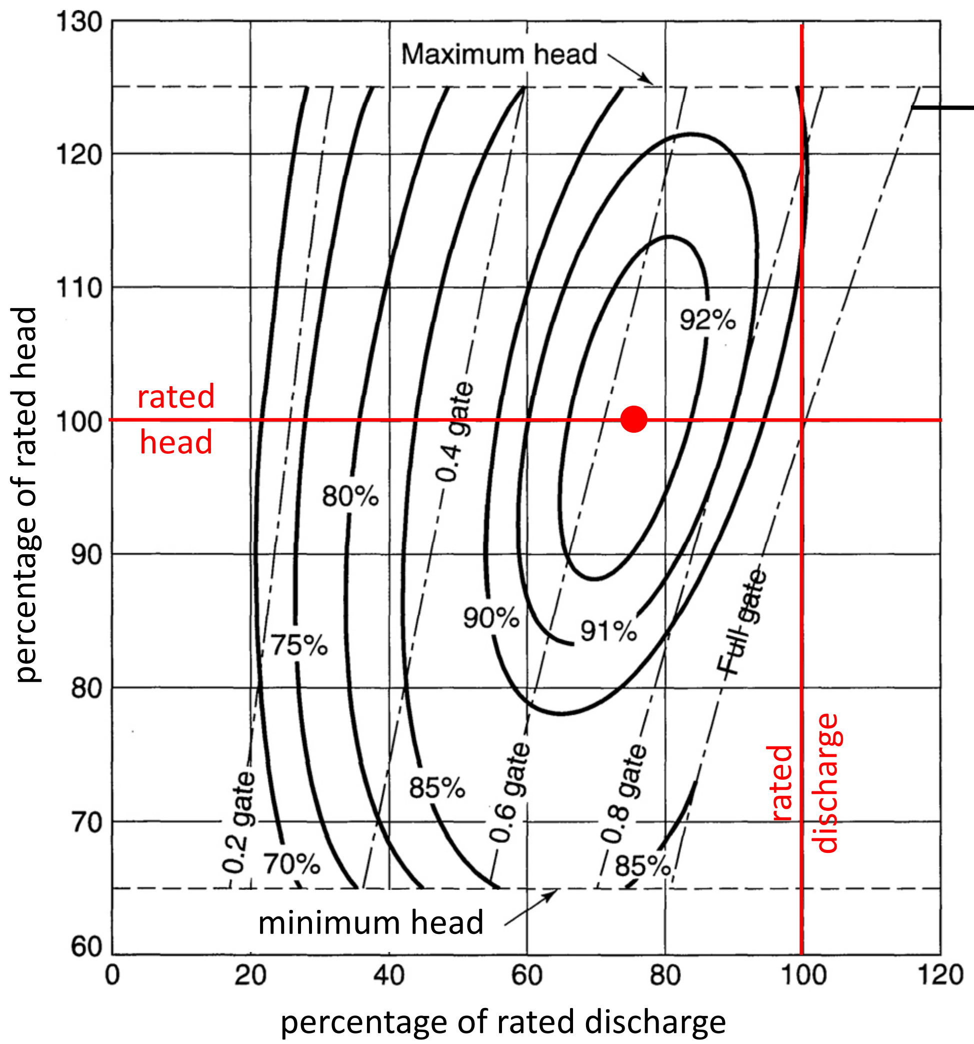
Kaplan turbine blades are adjustable.





Courtesy of A. Rinaldo

Francis turbine performance curve

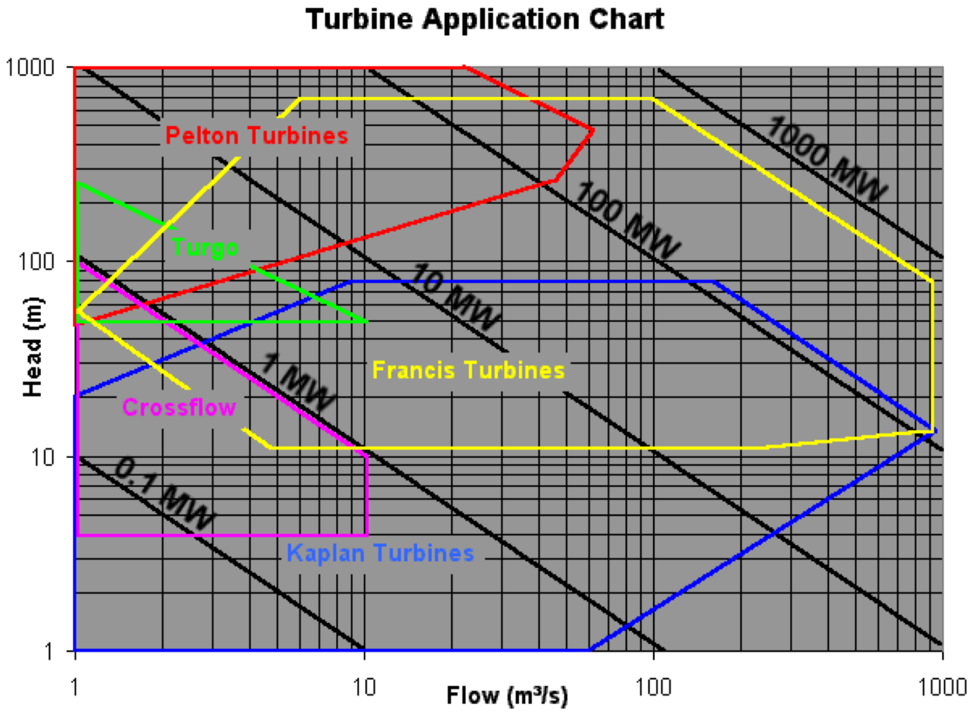


head-discharge curve for different gate opening

rated head: head at which efficiency is maximum

rated discharge: discharge at rated head with gate fully open. Note that the efficiency is not maximum at the rated discharge.

Range of application of different types of turbine



Pelton: high head and low flow;
Kaplan: low head and high flow;
Francis can cover a wide range of values.

Courtesy of A. Rinaldo

Take home messages from these three lectures

- L3.1 I remember (have understood) the meaning of energy grade line and hydraulic grade line and how to express losses
- L3.1 I remember the definition of friction factor, Reynolds number, mean shear stress and hydraulic radius
- L3.1 I know how to use the Moody diagram (chart) but not need to remember Coolebrook and White formula
- L3.1 I remember Darcy and Strickler formulas for fully developed turbulent flow in pipes
- L3.1 I can sketch energy aand grade line for pipe configurations and calculate the energy balance
- L3.1 I know the meaning of “hydraulically long” pipes

- L3.2 I understood and can expain the “three reservoirs” pipe design problem
- L3.2 I remember the condition expressing the optimal economic solution at pipe nodes
- L3.2 I understand how to design open branched networks
- L3.2 I understand how to design and verify closed loop networks

- L3.3 I know what a hydraulic machine does, its effect on energy and hydraulic grade lines and the functioning point
- L3.3 I can explain how pumps in parallel and in series work and how to control their functioning points
- L3.3 I can explain the start-stop problem
- L3.3 I know the different turbines and can calculate the power that can be extracted
- L3.3 I can explain the functioning of impulse (Pelton) turbines, including the equations.