ME 306 Fluid Mechanics II

Part 3

Turbomachinery

These presentations are prepared by

Dr. Cüneyt Sert

Department of Mechanical Engineering

Middle East Technical University

Ankara, Turkey

csert@metu.edu.tr

Fluid Machinery

- Fluid machinery is used to convert hydraulic energy to mechanical energy or vice versa.

Power absorbing	Power producing
Work is done on the fluid	Work is done by the fluid
Mechanical Energy → Hydraulic Energy	Hydraulic Energy → Mechanical Energy

Pump

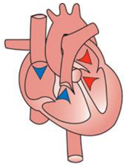
Turbine

Classification of Fluid Machinery

- Fluid machinery can be classified based on the motion of moving parts.

1) Positive Displacement Machines

- Fluid is directed into a closed volume.
- Energy transfer is accomplished by movement of the boundary of the closed volume.
- Closed volume expands and contracts, sucking the fluid in or pushing it out.



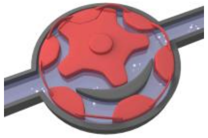
http://speakeasies.biz

Human heart

Water well pump

http://www.bicycleaccessories.us

Tire pump



http://en.wikipedia.org

Gear pump

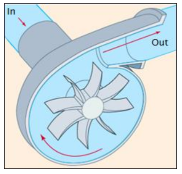
Classification of Fluid Machinery (cont'd)

2) Turbomachines

- Turbo means ''spin'' or ''whirl'' in Latin.
- Turbomachines use rotating shafts with attached blades, vanes, buckets, etc.
- In ME 306 we'll study turbomachines, mostly pumps.

http://en.wikipedia.org

Axial fan

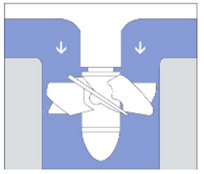


http://www.britannica.com

Centrifugal pump

http://www.noehill.com/nevada_county_california/cal1012.asp

Pelton wheel



Kaplan type hydraulic turbine

Classification of Turbomachines

Turbomachines

Power absorbing | Power producing

Incompressible | Compressible | Incompressible | Compressible

Pump

- Pumps increase the pressure of a liquid without changing its velocity considerably.
- Shown centrifugal (radial) pump is the most common type.
- Visit www.standartpompa.com to get more information on sizes and capacities.

Classification of Turbomachines (cont'd)

Turbomachines

Power absorbing | Power producing

Incompressible | Compressible | Incompressible | Compressible

Pump | Propeller

- Propellers are used to generate thrust.
- Marine propellers work with incompressible water and aircraft propellers work with compressible air.
- Pressure difference between the front and back surfaces of the blades create the thrust.

Classification of Turbomachines (cont'd)

Turbomachines

Power absorbing | Power producing

Incompressible | Compressible | Incompressible | Compressible

Pump | Propeller | Fan

- The main difference between fans, blowers and compressors is the pressure difference they create.
- Fans create small pressure difference. Their main purpose is to put high amount of fluid into motion.
- Shown is axial fan of a wind tunnel.

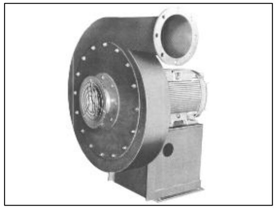
Classification of Turbomachines (cont'd)

Turbomachines

Power absorbing | Power producing

Incompressible | Compressible | Incompressible | Compressible

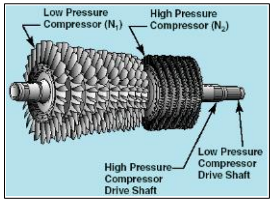
Pump | Propeller | Fan | Blower



- Blowers work with medium amout of flow rates and pressure ratios.
- They are mostly centrifugal type.
- Shown is an industrial type blower.

Classification of Turbomachines (cont'd)

- Turbomachines
  - Power absorbing
    - Incompressible
      - Pump
      - Propeller
    - Compressible
      - Fan
      - Blower
      - Compressor
  - Power producing
    - Incompressible
    - Compressible



- Compressors work with smaller flow rates, but create very high pressure ratios.
- Shown is a multi-stage axial compressor.
- Compressors are used in gas and steam turbines, natural gas pumping stations, turbochargers, refrigeration cycles, etc.

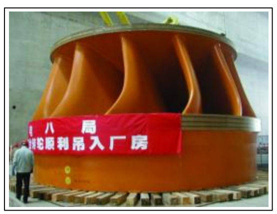
Classification of Turbomachines (cont'd)

- Turbomachines
  - Power absorbing
    - Incompressible
      - Pump
      - Propeller
    - Compressible
      - Fan
      - Blower
      - Compressor
  - Power producing
    - Incompressible
      - Pelton wheel
    - Compressible

- Pelton wheels have buckets attached to a rotating disk (wheel).
- They convert kinetic energy of a high speed liquid jet into mechanical energy.
- Largest ones used at hydraulic power plants have capacities up to 200 MW.

Classification of Turbomachines (cont'd)

- Turbomachines
  - Power absorbing
    - Incompressible
      - Pump
      - Propeller
    - Compressible
      - Fan
      - Blower
      - Compressor
  - Power producing
    - Incompressible
      - Pelton wheel
      - Hydraulic turbine
    - Compressible



- Hydraulic turbines are used at dams to generate electricity using high pressure water.
- Common types are Francis and Kaplan.
- Shown are the runner blades of the Francis turbines used at Three Gorges Dam / China.
- Atatürk Dam has a capacity of 8 x 300 MW.

Classification of Turbomachines (cont'd)

- Turbomachines
  - Power absorbing
    - Incompressible
      - Pump
      - Propeller
    - Compressible
      - Fan
      - Blower
      - Compressor
  - Power producing
    - Incompressible
      - Pelton wheel
      - Hydraulic turbine
    - Compressible
      - Steam turbine

- Steam turbines are used at power plants to generate electricity using high temperature and high pressure steam.
- 80 % of world's electricity is produced by steam turbines.
- Afşin-Elbistan thermal power plant has a capacity of 4 x 344 MW.

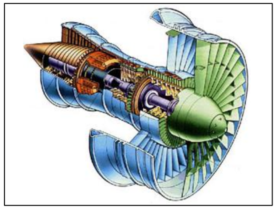
Classification of Turbomachines (cont'd)

Turbomachines

Power absorbing | Power producing

Incompressible | Compressible | Incompressible | Compressible

Pump | Propeller | Fan | Blower | Compressor | Pelton wheel | Hydraulic turbine | Steam turbine | Gas turbine



- Gas turbines are similar to steam turbines, but they use high temperature and high pressure combustion gases.
- A Boeing 777 is powered by 2 turbofan engines, each generting a thrust of ~500 kN.
- To learn how a turbofan engine operates visit http://www.youtube.com/watch?v=GpklBS3s7iU

Classification of Turbomachines (cont'd)

Turbomachines

Power absorbing | Power producing

Incompressible | Compressible | Incompressible | Compressible

Pump | Propeller | Fan | Blower | Compressor | Pelton wheel | Hydraulic turbine | Steam turbine | Gas turbine | Wind turbine

- As of 2017 Turkey's wind energy production is 6 GW. Total available capacity is 48 GW.
- World's total wind energy production is 490 GW, which is about 2.5 % of all electricity usage.
- There are wind turbines with more than 120 m rotor diameter, producing 6 MW of electricity (enough for 4500 homes) (http://www.youtube.com/watch?v=LQxp6QTjgJg)

Another Classification of Turbomachines

Turbomachines

Power absorbing | Power producing

Uncased | Cased | Impulse | Reaction

Axial Flow Propeller

- Uncased turbomachines do not have a solid casing around them.

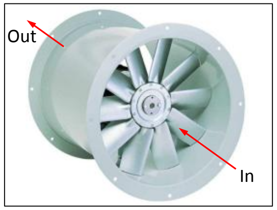
Another Classification of Turbomachines (cont'd)

Turbomachines

Power absorbing | Power producing

Uncased | Cased | Impulse | Reaction

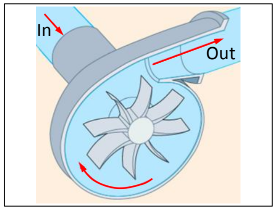
Axial Flow Propeller | Axial



- Fluid enters an axial flow turbomachine parallel to the axis of rotation.
- Fluid leaves the machine also in axial direction.

Another Classification of Turbomachines (cont'd)

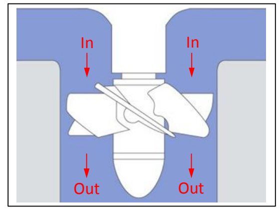
- Turbomachines
  - Power absorbing
    - Uncased
      - Axial Flow Propeller
    - Cased
      - Axial
      - Radial
  - Power producing
    - Impulse
    - Reaction



- In radial flow machines fluid intake is parallel to the axis of rotation.
- Rotating impeller blades push the fluid in radial direction.
- Fluid leaves the machine perpendicular to the rotation axis.

Another Classification of Turbomachines (cont'd)

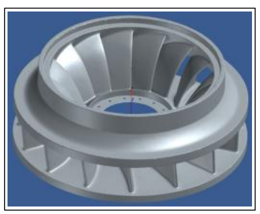
- Turbomachines
  - Power absorbing
    - Uncased
      - Axial Flow Propeller
    - Cased
      - Axial
      - Radial
      - Mixed
  - Power producing
    - Impulse
      - Pelton wheel
      - Wind turbine
    - Reaction
      - Axial (Kaplan)



- Kaplan turbines are axial flow machines.
- They are preferred for low head and high flow rate configurations.
- Their capacities are less than Francis type, less than 200 MW.
- They can provide efficiencies higher than 95 %.

Another Classification of Turbomachines (cont'd)

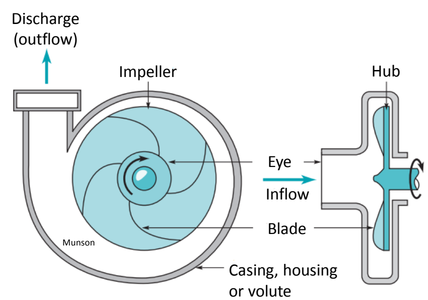
- Turbomachines
  - Power absorbing
    - Uncased
      - Axial Flow Propeller
    - Cased
      - Axial
      - Radial
      - Mixed
  - Power producing
    - Impulse
      - Pelton wheel
      - Wind turbine
    - Reaction
      - Axial (Kaplan)
      - Radial (Banki)
      - Mixed (Francis)

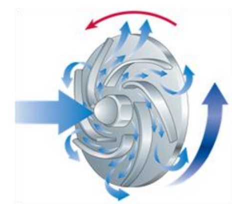


- Francis turbines are the most widely used turbomachines for hydropower.
- They are of mixed flow type.
- They can provide more than 800 MW power.
- For more information http://www.voithhydro.com

Centrifugal Pump

- Centrifugal pump is the most commonly used type of turbomachine.





Centrifugal Pump (cont'd)

- For centrifugal pump details watch

http://www.youtube.com/watch?v=9nL1XhKm9q8 (Principles and parts)
http://www.youtube.com/watch?v=Vq3hEe5jzSM (Pump Parts)
http://www.youtube.com/watch?v=UrChdDwHybY (Impeller animation)
http://www.youtube.com/watch?v=RvOzKhUDmJM (Computer aided blade design)

- Most important part is the impeller. It may have different designs such as
  - Backward-curved, radial or forward-curved
  - Closed (shrouded) or open

Open

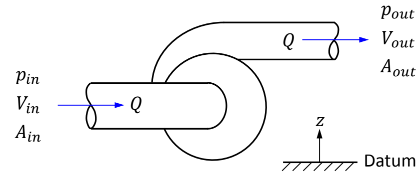
Called backward-curved if rotates in this direction

Called forward-curved if rotates in this direction

Open, radial

Closed (Shrouded)

Pump Head (h_s)



- Consider the BE between the inlet (suction) and outlet (discharge) of a pump.

$$\frac{p_{in}}{\rho g} + \frac{V_{in}^2}{2g} + z_{in} = \frac{p_{out}}{\rho g} + \frac{V_{out}^2}{2g} + z_{out} - h_s$$

Pump head

- Pump head is the difference between the total heads at the pump inlet and outlet.
- Pump head is a positive quantity with units of length.

Pump Head (cont'd)

- Elevation difference between inlet and outlet is generally negligibly small.
- If suction and discharge pipe diameters are the same $\rightarrow$ $V_{in} = V_{out}$
- For this simplified case

$$h_s = \frac{p_{out} - p_{in}}{\rho g} = \frac{\Delta p}{\rho g}$$

i.e. pump head is the pressure rise across the pump expressed as a head.

- Pump head is directly related to the power delivered to the fluid, known as water horsepower

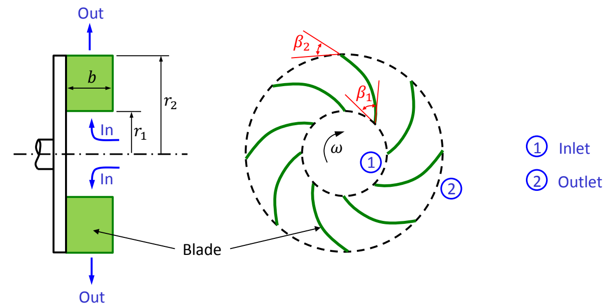
$$\mathcal{P}_f = \underbrace{\rho g Q}_{\text{Weight flow rate}} h_s$$

f for fluid

- Pump head can be defined as the power delivered to the fluid per weight of the fluid flowing through the pump in unit time (weight flow rate).

Theoretical Analysis of a Centrifugal Pump

Exercise: Consider the given schematic of a centrifugal pump. Perform a control volume analysis to derive a relation for the variation of the theoretical (ideal) pump head as a function of discharge (volumetric flow rate).



Theoretical Analysis of a Centrifugal Pump (cont'd)

Exercise: Water is pumped at a rate of 5300 L/min through a centrifugal pump operating at 1750 rpm. The impeller has a uniform blade height, b, of 5 cm with $r_1 = 4$ cm and $r_2 = 18$ cm, and exit blade angle β_2 is 23°. Assume ideal flow conditions and the tangential velocity component, $V_{1\theta}$, of the water entering the blade is zero. Determine

a) the tangential velocity component, $V_{2\theta}$, at the blade exit.

b) the ideal head rise

c) the power transferred to the fluid.

Reference : Munson

Pump Efficiency

- Power necessary to run the pump ($\mathcal{P}_p$), known as brake horsepower (bhp), is larger than power delivered to the fluid due to
  - mechanical and fluidic frictional losses
  - flow separation on impeller blade surfaces
  - misalignment of inlet flow velocity with impeller blade geometry
  - internal leakage, etc.

$$\mathcal{P}_p = T_{shaft}\,\omega > \mathcal{P}_f$$

p for pump

Torque supplied to the pump shaft

Rotational speed of the pump

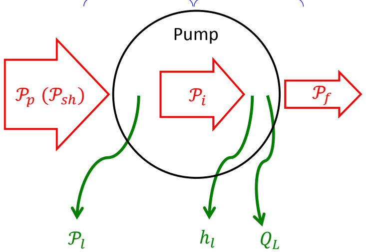
- Efficiency of the pump is defined as

$$\eta_p = \frac{\mathcal{P}_f}{\mathcal{P}_p} < 1$$

Pump Efficiency (cont'd)

$$\eta_p = \frac{\mathcal{P}_f}{\mathcal{P}_p}$$

$$\eta_m = \frac{\mathcal{P}_i}{\mathcal{P}_p} \qquad \eta_i = \frac{\mathcal{P}_f}{\mathcal{P}_i} = \eta_h \eta_v$$



$\mathcal{P}_p$ ($\mathcal{P}_{sh}$) : Pump power. Also called shaft power. Power input to the pump.

$\mathcal{P}_i$: Internal power

$\mathcal{P}_f$: Fluid power. Power delivered to the fluid.

$\mathcal{P}_l$: Mechanical power loss at bearings, etc.

h_l : Hydraulic friction loss (head loss)

Q_L : Leakage loss

η_m : Mechanical efficiency

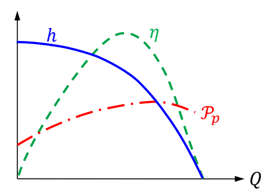
$\eta_i = \eta_h \eta_v$: Internal efficiency (Hydraulic eff. x Volumetric eff.)

$\eta_p = \eta_m \eta_h \eta_v$: Pump (overall) efficiency

Important Parameters of a Centrifugal Pump

• Volumetric flow rate (discharge, capacity)	Q
• Head	h_s (or simply h)
• Size (impeller diameter)	D
• Rotational speed	N [rpm] or ω [s^{-1}]
• Power consumption	$\mathcal{P}_p$
• Efficiency	η_p (or simply η)

- Fundamental characteristic curve of a pump is a plot of h vs. Q at a given rotational speed ω.
- It is customary to plot $\mathcal{P}_p$ and η on the same figure.

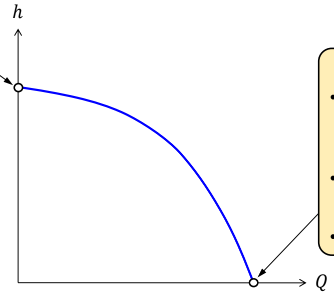


Pump Characteristic Curve

- $h - Q$ curve of a pump is known as its characteristic curve.
- A pump can operate only on its characteristic curve.
- At a given rotational speed (ω) a typical centrifugal pump characteristic curve is

Shutoff head

- Discharge valve of the pump is closed and $Q = 0$.
- Pump is not doing any useful work.
- $\mathcal{P}_f = 0$ & $\eta = 0$



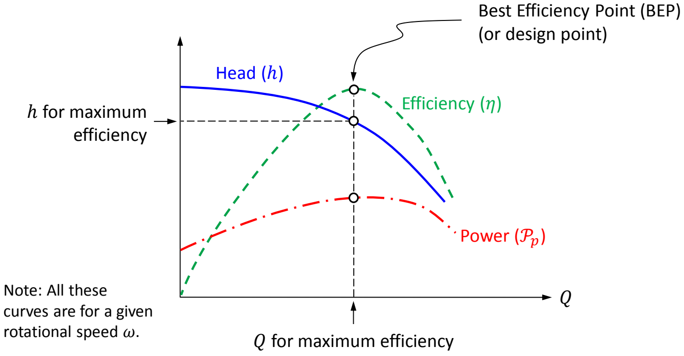
Free delivery

- There is no load on the pump and $h = 0$.
- Pump is not doing any useful work
- $\mathcal{P}_f = 0$ & $\eta = 0$

Note : This curve is for a given rotational speed.

Best Efficiency Point (BEP)

- The exact operation point of a pump depends on the system it is working in.
- Pumps are designed to work at (or close to) their maximum efficiency, but this is not always possible.



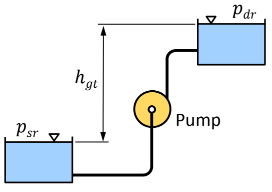
Note: All these curves are for a given rotational speed ω.

System Characteristic

- A pump works at an operating point on its characteristic curve.
- But this operating point depends on the system that the pump is installed in.
- Following pump works between a suction reservoir (sr) and a discharge reservoir (dr).
- BE between points sr and pr

$$\frac{p_{sr}}{\rho g} + \frac{V_{sr}^2}{2g} + z_{sr} = \frac{p_{dr}}{\rho g} + \frac{V_{dr}^2}{2g} + z_{dr} - h + h_f$$

Total major and minor losses



- If $p_{sr} = p_{dr} = p_{atm}$ and $V_{sr} = V_{dr} = 0$

$$h = h_{gt} + h_f$$

Total geometric head $(= z_{dr} - z_{sr})$

System Characteristic (cont'd)

- h_f consists of major and minor losses calculated as

Actual or equivalent pipe length

$$h_f = \sum_i \left(f_i \; \frac{L_i}{D_i} \; \frac{V_i^2}{2g} \right) + \sum_i \left(k_i \; \frac{V_i^2}{2g} \right)$$

Friction factor

Pipe diameter

Head loss coefficient for minor losses

- V_i's are average velocities in suction and discharge pipes.
- Using the continuity eqution $V_i = Q/A_i$

and the total loss becomes

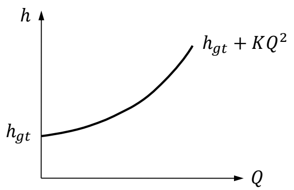
$$h_f = \sum_i f_i \frac{L_i}{D_i} \frac{Q^2}{2gA_i^2} + \sum_i k_i \frac{Q^2}{2gA_i^2}$$

or simply $h_f = KQ^2$

System Characteristic (cont'd)

- Using this h_f in the BE we get the following system characteristic equation

$$\boxed{h = h_{gt} + KQ^2}$$



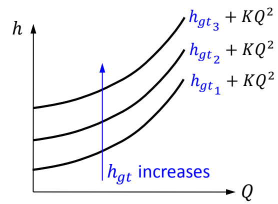
- Minimum head the pump should provide is equal to the total geometric head.
- Additional pump head is necessary to overcome frictional losses. This part increases with the square of the flow rate.

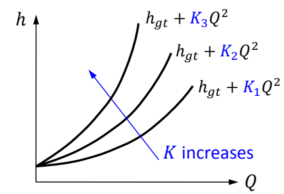
System Characteristic (cont'd)

- It is possible to change system characteristic in two ways.

Total geometric head (h_{gt}, the difference between reservoir levels) can be changed.

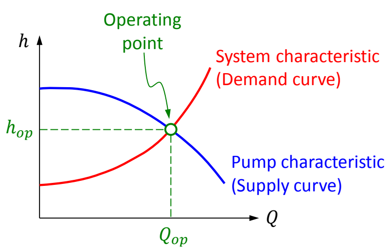
Friction loss can be changed by changing K. For example by opening or closing a valve.





Operating Point

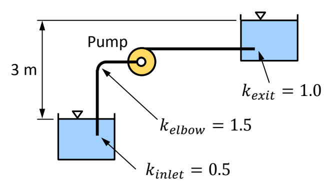
- A pump installed on a system will not work at an arbitrary point.
- It will operate at the point where pump and system characteristics intersect.

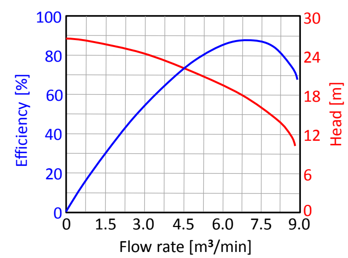


- Normally we want the operating point to be close to the BEP (design point).
- However BEP is not always the most economical operating point as far as the power consumption is concerned, i.e. BEP is not necessarily the minimum $\mathcal{P}_p$ point.

Operating Point (cont'd)

Exercise: Water is pumped from one large open tank to a second one. The pipe diameter throughout is 15 cm and the total length of the pipe between the pipe entrance and the exit is 60 m. Minor loss coefficients for the entrance, exit and the elbow are shown and the friction factor for the pipe can be taken as 0.02. A certain centrifugal pump with the shown characteristic is suggested for this flow system. With this pump, what would be the flow rate? Do you think this pump is a good choice? (Reference: Munson)





Similarity Laws for Pumps

- Similitude analysis is typically used
  - to predict the performance of a pump when a different sized impeller is used in the same casing.
  - to predict the performance of a pump when it operates at a different speed.

- Perform a Buckingham-Pi analysis with the following parameters

$$Q\,,\;\; gh\,,\;\; D\,,\;\; \mathcal{P}_p\,,\;\; \omega\,,\;\; \rho\,,\;\; \mu$$

to get the following non-dimensional groups

Flow coefficient : $\pi_Q = \dfrac{Q}{\omega D^3}$

Head coefficient : $\pi_h = \dfrac{gh}{\omega^2 D^2}$

Power coefficient : $\pi_{\mathcal{P}} = \dfrac{\mathcal{P}_p}{\rho \omega^3 D^5}$

Reynolds number : $\pi_\mu = \dfrac{\mu}{\rho \omega D^2} = \dfrac{1}{Re}$

Similarity Laws for Pumps (cont'd)

- In most pump applications similarity of viscous forces are not as important as the other π groups.
- Two geometrically similar pumps are said to be operating under similar conditions if the remaining three π groups are equal.

$$\underbrace{\pi_{Q_1} = \pi_{Q_2}\;, \qquad \pi_{h_1} = \pi_{h_2}\;, \qquad \pi_{\mathcal{P}_1} = \pi_{\mathcal{P}_2}}_{\text{Affinity laws}}$$

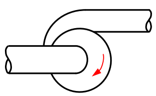
where 1 and 2 are two similar operating points (homologous points).

Exercise : Show that when affinity laws are satisfied, efficiencies of two homologous points are equal.

Exercise : How does the nondimensional performance curve (π_h vs. π_Q) of two geometrically similar pumps compare with each other? What about $\pi_{\mathcal{P}}$ vs. π_Q and η vs. π_Q curves?

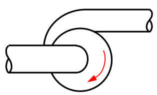
Similarity Case 1 – Different Rotational Speeds

- Consider a pump with a known performance. We want to determine its operation at a different speed.



Delivering Q_1 and h_1
Using $\mathcal{P}_{p_1}$

$D_1 = D_2$
$\omega_1 \neq \omega_2$



Delivering Q_2 and h_2
Using $\mathcal{P}_{p_2}$

- Pump sizes are the same ($D_1 = D_2$). Affinity laws are simplified as follows

$$\frac{Q_1}{Q_2} = \frac{\omega_1}{\omega_2}\;, \qquad \frac{h_1}{h_2} = \left(\frac{\omega_1}{\omega_2}\right)^2\;, \qquad \frac{\mathcal{P}_{p_1}}{\mathcal{P}_{p_2}} = \left(\frac{\omega_1}{\omega_2}\right)^3$$

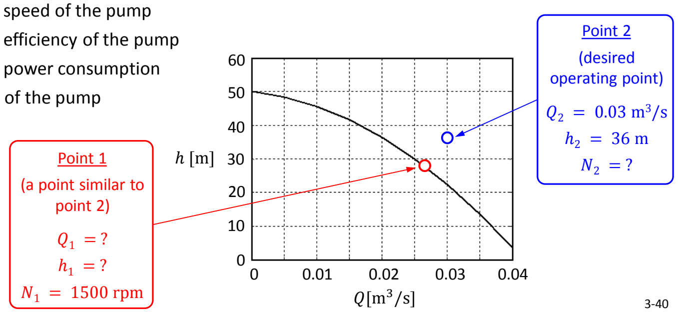
Similarity Case 1 (cont'd)

Exercise : Head and efficiency of a centrifugal pump running at 1500 rpm are given as

$$h \;=\; 50 - 200\,Q - 24000\,Q^2$$
$$\eta \;=\; 60\,Q - 1200\,Q^2$$

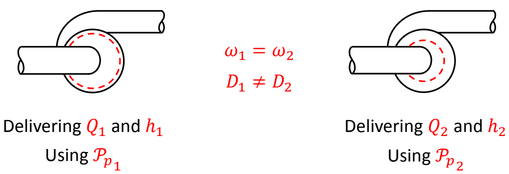
It is desired to deliver 0.03 m³/s of water against a head of 36 m. Determine

a) speed of the pump
b) efficiency of the pump
c) power consumption of the pump



Similarity Case 2 – Different Sizes (Impeller Diameters)

- Consider a pump with a known performance. We want to study the operation of a similar pump with a different impeller size rotating at the same speed.



- Rotational speeds are the same ($\omega_1 = \omega_2$). Affinity laws simplify as follows

$$\frac{Q_1}{Q_2} = \left(\frac{D_1}{D_2}\right)^3 \quad , \quad \frac{h_1}{h_2} = \left(\frac{D_1}{D_2}\right)^2 \quad , \quad \frac{\mathcal{P}_{p_1}}{\mathcal{P}_{p_2}} = \left(\frac{D_1}{D_2}\right)^5$$

Similarity Case 2 (cont'd)

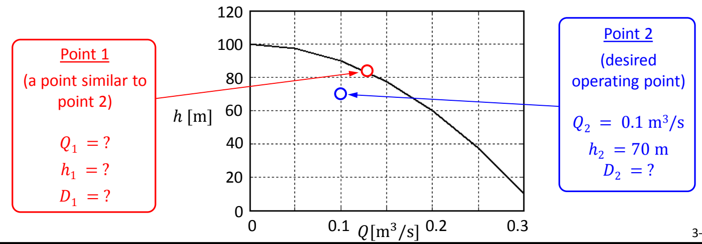
Exercise : Characteristic curve of a centrifugal pump is given as

$$h = 100 - 1000\, Q^2$$

It is desired to deliver 0.1 m³/s of water against a head of 70 m. For these requirements it is thought that using a similar pump with a smaller impeller would be more efficient.

a) Determine the required percent reduction in impeller diameter.

b) Determine the percent decrease in power consumption.



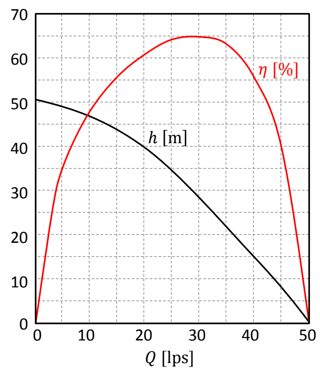
System Characteristic, Operating Point & Similarity

Exercise : Characteristics of a centrifugal pump at 600 rpm is given below. The pump is used to elevate water by 32 m from a lake to an open tank. Flow rate is measured as 22 lps while the delivery valve is fully open and the pump running at 600 rpm.

Determine the power consumption for the following operations.

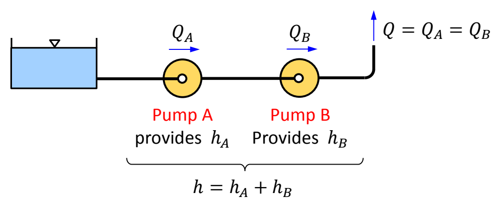
a) Valve closure is increased such that the frictional loss is doubled.

b) Pump speed is increased to 720 rpm while keeping the valve fully open.



Series Combination of Pumps

- Series combination is used if the head provided by a single pump is not enough.



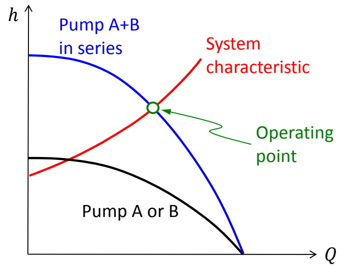
- Same Q goes through both pumps.
- Total head provided is the sum of individual heads.
- Pumps can be identical or different.
- More than two pumps can be combined in series.

Series Combination of Pumps (cont'd)

Exercise : Show that for two pumps combined in series overall efficiency is

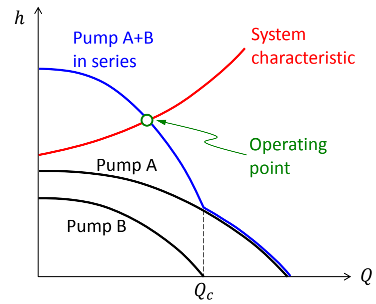
$$\eta = \frac{h_A + h_B}{\dfrac{h_A}{\eta_A} + \dfrac{h_B}{\eta_B}}$$

- To get combined pump characteristic, individual pump characteristics are added vertically.
- If the pumps are identical



Series Combination of Pumps (cont'd)

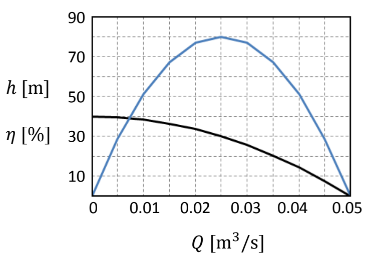
- If the pumps are NOT identical



- Above a certain Q_c pump B is forced to operate above its free delivery point. For such a case it just creates extra loss and should be shut off and bypassed.

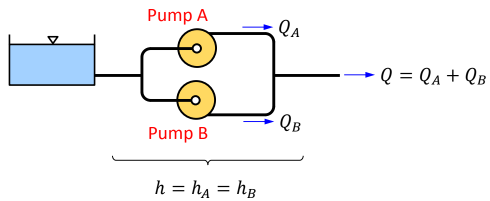
Series Combination of Pumps (cont'd)

Exercise : Two identical pumps, with shown characteristics, are combined in series and used to transport water between two reservoirs with an elevation difference of $z_{dr} - z_{sr} = 50$ m. Total length of suction and discharge pipes is 120 m. Pipe diameters are 0.12 m. Friction factor inside the pipes is 0.022. Neglecting the minor losses, determine the power required to drive both pumps.



Parallel Combination of Pumps

- Parallel combination is used if the flow rate provided by a single pump is not enough.



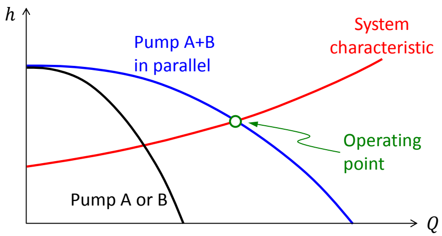
- Each pump provides the same head h.
- Total flow rate is the sum of individual flow rates.
- Pumps can be identical or different.
- More than two pumps can be combined in parallel.

Parallel Combination of Pumps (cont'd)

Exercise : Show that for two pumps combined in parallel overall efficiency is

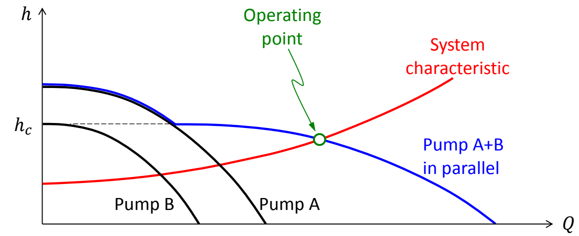
$$\eta = \frac{Q_A + Q_B}{\frac{Q_A}{\eta_A} + \frac{Q_B}{\eta_B}}$$

- To get combined pump characteristic, individual pump characteristics are added horizontally.
- If the pumps are identical



Parallel Combination of Pumps (cont'd)

- If the pumps are NOT identical



- Above a certain h_c pump B is forced to operate above its shutoff head. For such a case it just creates extra loss and should be shut off and its branch should be blocked with a valve.

Cavitation

- In a liquid flow cavitation occurs when the local static pressure falls below the vapor pressure of the liquid.
- For a cavitating flow
  - liquid locally vaporizes forming bubbles.
  - bubbles collapse as they travel to higher pressure regions and cause erosion/surface pitting.
  - flow becomes unsteady, causing noise and vibration.
  - performance of the turbomachine drops.
- For a pump, critical low pressure region is the entrance, and for a turbine it is the exit.
- High speed regions like propeller blade tips are also critical.
- Listen to the sound of a cavitating pump : www.youtube.com/watch?v=Qw97DkOYYrg
- Watch propeller tip cavitation : www.youtube.com/watch?v=GpklBS3s7iU

Cavitation Damage

Damage on Francis turbine blades

Damage on centrifugal pump impeller

Damage on propeller blades

Cavitation of a Pump and $NPSH$

- Cavitation possibility of a pump is checked using Net Positive Suction Head ($NPSH$).
- $NPSH$ is the difference between the total head at the suction side and the head corresponding to the vapor pressure.

Suction velocity

Suction pressure

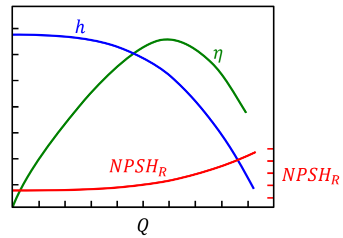
Vapor pressure

$$NPSH = \underbrace{\frac{p_s}{\rho g} + \frac{V_s^2}{2g}}_{\text{Total head at the suction side of the pump (Datum is arranged so that } z_s = 0)} - \frac{p_v}{\rho g}$$

- Point s denotes the suction side (inlet) of the pump.
- It is used in the definition because it is the critical low pressure region.

NPSH (cont'd)

- There are two values of $NPSH$ that we work with
  - $NPSH$ required ($NPSH_R$)
  - $NPSH$ available ($NPSH_A$)
- $NPSH_R$ is the value that must be exceeded to prevent cavitation inside the pump.
- It is measured by the manufacturer of the pump and provided as an extra curve on the pump characteristic plot.



NPSH (cont'd)

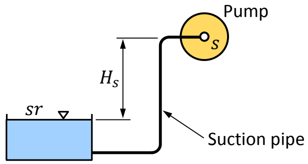
- $NPSH_A$ is the value that we need to calculate for the problem of interest.
- Consider the BE for the suction side of a pump

$$\frac{p_{sr}}{\rho g} + \frac{V_{sr}^2}{2g} + z_{sr} = \frac{p_s}{\rho g} + \frac{V_s^2}{2g} + z_s + h_{fs}$$

Typically $\quad p_{sr} = p_{atm}$, $\quad V_{sr} = 0$

$z_s - z_{sr} = H_s$

h_{fs} : Frictional losses at the suction side of the system



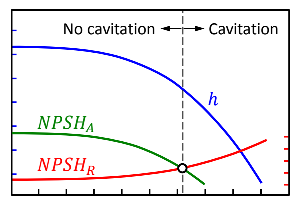
$$\frac{p_s}{\rho g} + \frac{V_s^2}{2g} = \frac{p_{atm}}{\rho g} - h_{fs} - H_s \quad \rightarrow \quad NPSH_A = \frac{p_{atm} - p_v}{\rho g} - h_{fs} - H_s$$

NPSH (cont'd)

$NPSH_R =$ Provided by the manufacturer , $\quad NPSH_A = \dfrac{p_{atm} - p_v}{\rho g} - h_{fs} - H_s$

- To prevent cavitation

$NPSH_A \geq NPSH_R$



Exercise : What can be done to make $NPSH_A$ larger for the pump shown in the previous slide?

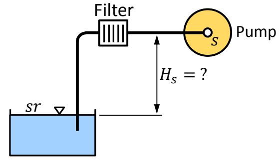
Exercise : How does the vapor pressure of water change with temperature? What does this information tell us about preventing cavitation?

NPSH (cont'd)

Exercise : A centrifugal pump is to be placed above a large open water tank to pump water at a flow rate of $1.4 \times 10^{-2}\ \mathrm{m^3/s}$. At this flow rate the required NPSH value is given as 4.5 m by the pump manufacturer. Water temperature is 30 °C and the atmospheric pressure is 95 kPa. Suction side pipe is short and the main head loss between the suction tank and the pump is due to a filter that has a head loss coefficient of $k = 20$. Other losses can be neglected. Suction pipe diameter is 10 cm.

a) Determine the maximum height that the pump can be located above the water surface of the suction tank without cavitation.
b) If you were required to place a valve in the flow path to regulate the flow rate, would you place it upstream or downstream of the pump? Why?

(Munson's book)

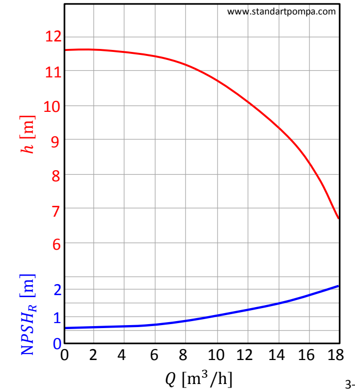


NPSH (cont'd)

Exercise : Centrifugal pump with the given characteristic is running at 1450 rpm to pump water at 25 °C from a reservoir whose surface is 1.2 m above the centerline of the pump inlet. Reservoir is open to atmospheric pressure.

The piping system from the reservoir to the pump consists of 3.2 m of cast iron pipe with a diameter of 5 cm and an average roughness of 0.05 cm. Minor losses at the suction side of the pump are; sharp edged inlet ($k = 0.5$), three flanged smooth 90° elbows ($k = 0.3$ each) and a fully open flanged globe valve ($k = 6$).

Estimate the maximum flow rate that can be pumped without cavitation.



Pump Specific Speed (N_s)

- Specific speed is a useful non-dimensional pi-term obtained by combination π_Q and π_h to eliminate D.

$$N_s = \frac{(\pi_Q)^{1/2}}{(\pi_h)^{3/4}} = \frac{\omega\sqrt{Q}}{(gh)^{3/4}}$$

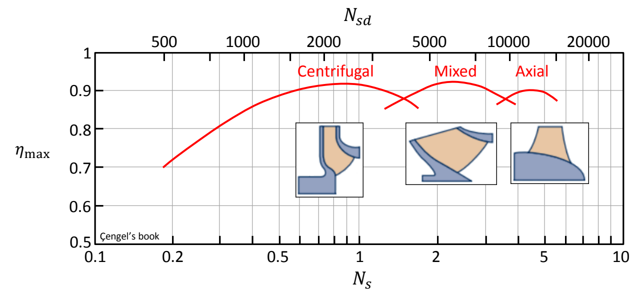
- In the industry the following dimensional form is also commonly used

$$N_{s_d} = \frac{\omega(\mathrm{rpm})\sqrt{Q(\mathrm{liter/min})}}{[h(\mathrm{m})]^{3/4}}$$ (Note that g is missing)

where $N_{s_d} = 2733\ N_s$

- N_s is useful to classify and compare different types of pumps at their BEP.
- N_s is mainly used for preliminary pump selection.

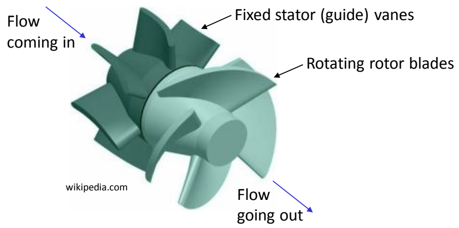
Pump Specific Speed (cont'd)



- Centrifugal (radial) pumps work efficiently at low specific speeds ($N_s < 1.5$).
- Mixed pumps work efficiently at medium specific speeds ($1.5 < N_s < 3.5$).
- Axial (propeller) pumps work efficiently at high specific speeds ($N_s > 3.5$).

Axial Pumps (Propeller Pumps)

- Centrifugal pumps are usually work efficiently at high h and low Q.
- Certain applications, such as drainage and irrigation involve low h and high Q.



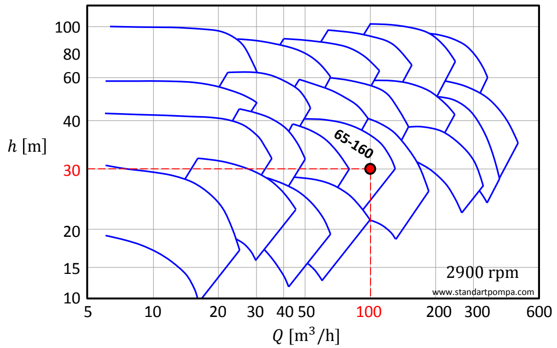
- World's most powerful pump: http://pressurewashr.com/the-worlds-most-powerful-water-pump/

Pump Selection

- Two main inputs for pump selection are
  - required head, h.
  - required flow rate, Q.
- Additional considerations for pump selection are
  - pump speed
  - type of fluid (highly viscous, muddy, etc.)
  - available space, vertical placement limitations, etc. that will affect $NPSH_A$
  - maximum allowable noise level
  - etc.
- For preliminary pump selection specific speed (N_s) is commonly used.

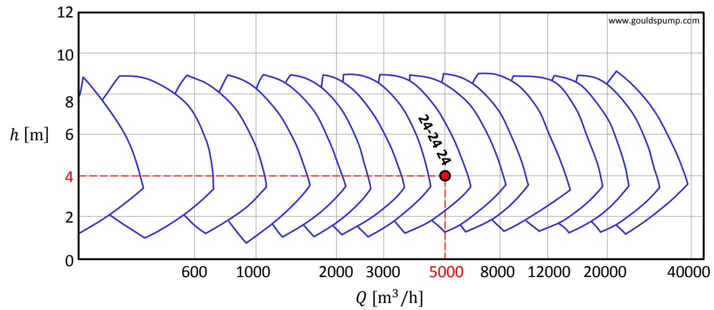
Pump Selection (cont'd)

- Manufacturers provide catalogues of their pumps.
- Following chart is for centrifugal pumps produced by Standart Pompa.
- For an application with $Q = 100\ \mathrm{m^3/h}$ and $h = 30\ \mathrm{m}$, ''65-160'' family seems suitable.



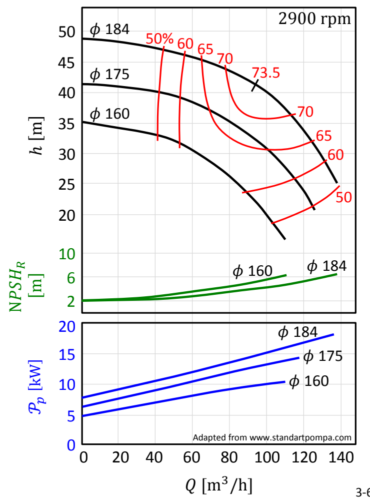
Pump Selection (cont'd)

- This one is for axial pumps produced by Goulds Pumps.
- For an application with $Q = 5000\ \mathrm{m^3/h}$ and $h = 4\ \mathrm{m}$, ''24-24 24'' family seems suitable.

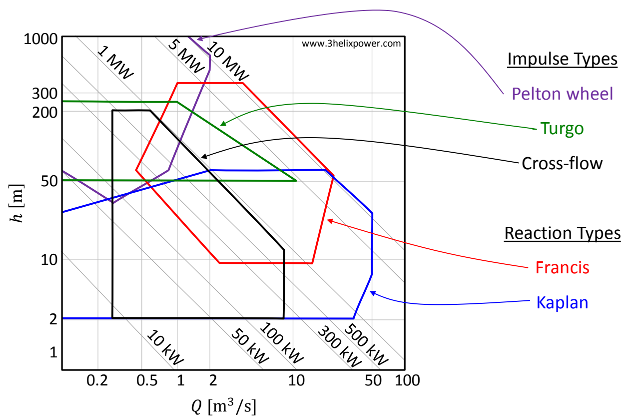


Pump Selection (cont'd)

- These are the detailed performance curves of the the pumps in the ''65-160'' family of Standart Pompa.
- There are three similar pumps with impeller diameters of 160 mm, 175 mm and 184 mm.
- Red curves are iso-efficincy lines.
- $NPSH_R$ and $\mathcal{P}_p$ curves are also provided.
- One of these three pumps can be selected by considering cavitation possibility, efficiency and power consumption.
- The smallest pump cannot provide the required head of 30 m at the desired flow rate of 100 m^3/h.

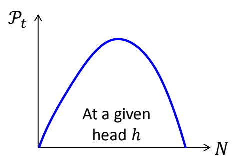


Turbines



Turbines (cont'd)

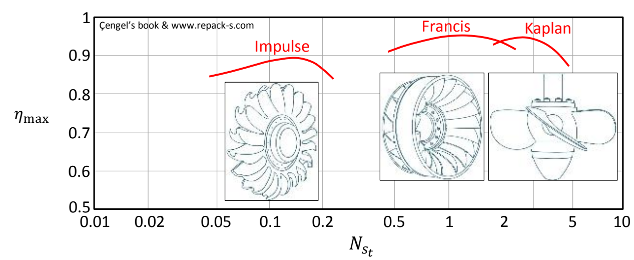
- Fundamental performance characteristic of a turbine is the power produced ($\mathcal{P}_t$) vs. rotational speed curve at a given head.



- Affinity laws used for pumps are valid for turbines too.
- Turbine specific speed can be used for preliminary turbine selection. It is defined in a slightly different way than pumps

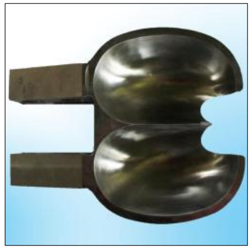
$$N_{s_t} = \frac{(\pi_{\mathcal{P}})^{1/2}}{(\pi_h)^{5/4}} = \frac{\omega\sqrt{\mathcal{P}_t}}{\sqrt{\rho}\ (gh)^{5/4}}$$

Turbine Specific Speed (N_{s_t})



- Impulse turbines work efficiently at low specific speed ($N_{s_t} < 0.3$) (High h, low Q).
- Francis turbines work efficiently at medium specific speeds ($0.3 < N_{s_t} < 2$).
- Kaplan turbines work efficiently at high specific speeds ($N_{s_t} > 2$) (Low h, high Q).

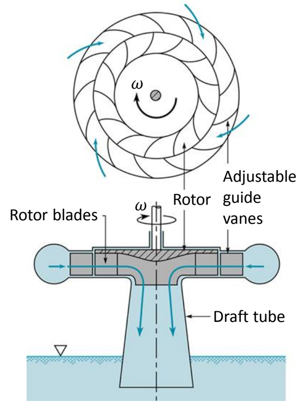
Pelton Wheel



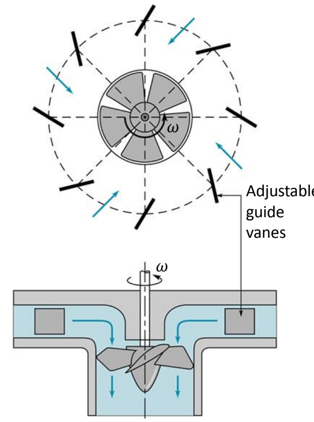
Typical bucket design

- Compare Pelton, Kaplan and Francis turbines: https://www.youtube.com/watch?v=k0BLOKEZ3KU

Francis and Kaplan Turbines

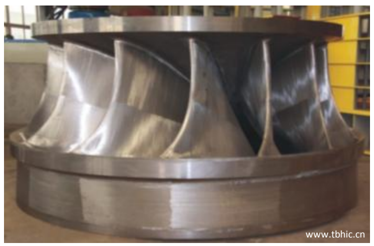


Francis turbine
(radial flow)



Kaplan turbine
(axial flow)

Francis and Kaplan Turbines (cont'd)



Runner of a Francis turbine

Runner of a Kaplan turbine

- Francis turbine: https://www.youtube.com/watch?v=3BCiFeykRzo
  https://www.youtube.com/watch?v=IZdiWBEzISM
- Kaplan turbine: https://www.youtube.com/watch?v=0p03UTgpnDU
  https://www.youtube.com/watch?v=_eLufvzh5HU

Turbines (cont'd)

Exercise: A Francis turbine is being designed for a hydroelectric dam. Instead of starting from scratch, the engineers decide to geometrically scale up a previously designed turbine that has an excellent performance history. The existing turbine (turbine A) has diameter D_A = 2.05 m, and spins at N_A = 120 rpm. At its best efficiency point, Q_A = 350 m³/s, h_A =75 m $\mathcal{P}_t$ = 242 MW. The new turbine (turbine B) is for a larger facility. Its generator will spin at the same speed (120 rpm), but its net head will be higher (h_B = 104 m).

a) Calculate the diameter (D_B) of the new turbine such that it operates most efficiently, and calculate Q_B, and η_B.

b) Calculate the turbine specific speeds of both turbines.

Turbines (cont'd)

Exercise : Calculate the specific speeds of the following turbines

a) Francis type radial flow turbine at the Round Butte hydroelectric power station in Madras rotating at 180 rpm and producing 119 MW of power at a flow rate of $127 \text{ m}^3/\text{s}$ from a head of 105 m.

b) Francis type mixed flow turbine at the Smith Mountain hydroelectric power station in Roanoke, VA, rotating at 100 rpm and producing 194 MW of power at a flow rate of $375 \text{ m}^3/\text{s}$ from a head of 54.9 m.

c) Kaplan type axial flow turbine at the Warwick hydroelectric power station in Cordele, GA, rotating at 100 rpm and producing 5.37 MW of power at a flow rate of $63.7 \text{ m}^3/\text{s}$ from a head of 9.75 m.

Exercise : Learn the meaning of the following turbine related terms

Runner blade, wicket gate, stay vane, crown, penstock, draft tube, tail water

Exercise : How does hydraulic power work? http://www.youtube.com/watch?v=cEL7yc8R42k

Virtual turbines http://www.youtube.com/watch?v=HzQPNpP55xQ