Pumps, Turbines, and Pipe Networks, part 2

Ch 11 Young
Pump and Turbine Dimensional Analysis (11.5 Young)

• Say we want to replace turbines on the Hoover Dam

• Want to have a good design
  – Essentially impossible to build, test, and modify at full scale
  – Design and testing for reduced scale to determine performance characteristics

• Can scale up to prototype for prediction of performance as installed
Dimensionless Groups

- Dimensional analysis is used for homologous pumps (same geometries but different sizes) and create dimensionless groups
  - Head rise coefficient
  - Power coefficient (shaft power)
  - Flow coefficient (discharge)
  - Efficiency (linearly related to other three)
• Ex 11.4
– 8 in diameter pump, 1200RPM
– What are head, required power?

1000 RPM
Curves for 12 inch pump

(a)
Specific Speed

• Make dimensionless Pi term related to rate of rotation: also uses Q, g, h_a – not D
  – Specific speed, \( N_s \)
    • Given near most efficient point
  – Different pumps work best in different specific speed ranges: tells you the type of pump needed
    • Low specific speed (high head, low flow): Radial
    • Medium specific speed: mixed flow
    • Large Specific speed (low head, high flow): axial
Dimensional Specific Speed

- US customary units for pumps: gpm, rpm, ft
  - Calculate specific speed with these units
  - Differs by constant factor of 2733 from $N_s$
  - Has dimensions, not dimensionless
  - Many other definitions using different units
  - Be careful
Types of Pumps vs Specific Speed

Specific speed, $N_{sd}$

Radial flow
- Impeller shrouds
- Hub
- Vanes

Mixed flow
- Impeller shrouds
- Hub
- Vanes

Axial flow
- Impeller hub
- Impeller shrouds

Specific speed, $N_s$

0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0

Axis of rotation
Axial and Mixed Flow Pumps
11.6 Young

• Centrifugal pumps work only over a certain range of specific speeds
  – Not as good for very high flow, low head applications (e.g. irrigation)
  – Use axial-flow pumps here
  – Look like propellers
  – Specific speeds $N_{sd} > 9000$
  – Quite different flow characteristics
• Centrifugal pumps
  – HP is largest for large flows

• Axial Pumps
  – HP is largest for zero flow
  – Can lead to difficulties during startup if not careful
  – May not have enough power to work pump at low flow rates
Other types of pumps

• Positive displacement
  – Traps air, water and forces it through the line
  – Some sump pumps, especially for long suction lengths
  – Self-priming, known volume pumped
  – Bicycle pump is a simple example of a positive displacement pump
  – Reciprocating, rotary, many designs
  – Small volumetric flow rates
Positive Displacement Piston Reciprocating Pump
Positive Displacement Vane Pump
Turbines

- Widely used for power generation
- Efficiencies generally greater than 90% for large installations
- Two general types
  - Impulse turbines (relying on velocity of jet)
    - Pelton Wheel
  - Reaction turbines (completely submerged, pressure drop across turbine)
    - Francis Turbine
    - Kaplan Turbine
    - Many other designs
Pelton Wheel

• Easiest to understand
• Invented in California late 1800s
• High head, low flow
• Water flows from nozzle, reverses direction in Pelton wheel buckets, exits
• Must be placed a small elevation above downstream water level
• May have 6 or more nozzles to balance load
Modern 6-nozzle Pelton Wheel

From Pelton’s original patent application
Pelton Wheel Movie

Old Pelton Wheel from California gold rush
Pelton Wheel Theory

- Follows directly from Moment-of-Momentum theory
  - Flow in and flow out are at same radius
    - Inward angle purely tangential
    - Outward angle almost tangential backwards
  - Zero power for no rotation, free rotation
  - Maximum power for intermediate rate of rotation
Francis Turbine

• Very common medium head, medium flow (medium specific speed) including for very large installations
  – Hoover Dam, Three Gorges (China), Itaipu Dam (Brazil)
  – Efficiencies greater than 90%
Francis turbine

Kaplan turbine
• Hoover Dam
  – 520ft head (158m) (average)
  – 2,080 MW (2.08 GigaWatts)
  – 17 Francis Turbines for main generating capacity

• Itaipu Dam (Brazil)
  – 120m head
  – 24,000MW installed
  – 20 Francis turbines (18 on at a time)

• Three Gorges (China)
  – 80.6m head
  – 22,500 MW
  – 32 Francis main turbines
Kaplan Turbine

• Axial flow – looks much like a propeller but has variable blade angle
• High specific speeds – low head, high flow
• Can have flow come in from sides
• Also very efficient >90% efficiency
Turbine Specific Speed

- Different from Pump Specific Speed
  - Power replaces volumetric flow rate
  - Tells (broadly) what type of turbine to use
Turbine Cavitation

- If water pressure drops below vapor pressure at any point, cavitation will occur
  - Not a big problem upstream of turbine
  - In reaction turbines high velocities, combined with lower pressures at downstream end
  - Need to seat turbines as low as possible to ensure do not get near cavitation pressures
  - No problems in impulse turbines (Pelton Wheel)
  - Very similar to cavitation in pumps
Draft Tube

- Water exiting turbine will have significant velocity
- Want to recover velocity head before exiting downstream to minimize losses
- Draft tube slows water gradually

Francis turbine draft tube

Draft tubes for Nepalese installation
Wind Turbines

- Wind turbines are becoming increasingly more important as costs decrease and the price of other materials (e.g. oil) increases.
- Installed capacity increasing rapidly.
- Available power proportional to $V^3$: economics improve greatly in windy areas.
- Both similarities and differences from hydroelectric turbines.

Present Day Capacity
Present Capacity

Q3 2018 Installed Wind Power Capacity (MW)

Total Installed Wind Capacity: 90,550 MW

Source: American Wind Energy Association Market Report
Types of Turbines

- Generally divided into Horizontal Axis (HAWT) and Vertical Axis (VAWT)

Wind Turbine Theory

- The major distinctive factor for wind turbines is that flow is not confined to a pipe
  - Pressure is the same far upstream and far downstream of the turbine
- How, then is energy extracted?
• Wind turbines can only extract energy by having a larger downwind flow area than upwind.
  • Consequence of equal pressure while energy is extracted.
• Can use this plus Bernoulli to find maximum possible efficiency of wind turbines.
Velocity and Pressure Variations

Distance

Velocity

Pressure

1

2

3

4
Maximum Wind Turbine Efficiency

- Use Bernoulli, conservation of momentum, mass equations
- Find efficiency of turbine compared to available wind power
- Varies with (not well known) ratio upstream, turbine areas
- Maximum $C_p \approx 0.59$
- Betz Limit
- Actual efficiency will be less from other losses

$A_1/A_3 = 1$

$A_1/A_3 = 0$
Actual Turbine Efficiency

• Different efficiencies for different designs
• None reach the theoretical limits
• Higher efficiency leads to higher power – higher profits
• Root cause is that the air is not confined into a pipe, so it can seek its own shape