ChE 374–Lecture 32–Turbines

- Pumps add mechanical Energy to increase the fluid head. Turbines EXTRACT mechanical energy at the expense of fluid head (decreased pressure).
- Turbine types:
  - Hydraulic, wind, steam, gas.
  - Typically more efficient than pumps (larger, less separation, lower speed, narrower operating range).
- 2 Types: Positive displacement (for flow measurement), and DYNAMIC (our focus, for power production).
  - Dynamic: pumps have *impellers*, turbines have *runners*.
    * 2 types: Impulse and Reaction.
- Impules turbines (Pelton Wheel)
  - High Head, Low Flow.
  - Fluid through nozzle, deflected in a wheel of buckets. Pressure is converted to kinetic energy, that impinges on and rotates the bucket wheel.
  - Analyse with a momentum balance.
    * Optimal redirection angle is 180^o in theory, and 160^o as a practical compromise.
    * Optimal bucket speed is $u = V_j/3$, where V_j is the jet velocity. (Book says its $u = V_j/2$).
    * Efficiencies up to 90%
- Reaction Turbines.
  - As for pumps, have Centrifugal, Mixed Flow, and Axial.
  - 2 Types: Fracis and Kaplan
    * Francis: Radial and Mixed Flow: Med. Head and Med. Flow.
    * Kaplan: Axial Flow (propeller with variable pitch): Low Head, High Flow.
    * $\eta = \text{bhp}/\rho g H \dot{V}$.
- Wind Turbines:
  - $\dot{W}_{\text{avail}} = \text{K.E. x flow rate} = \frac{1}{2}v^2\dot{m} = \frac{1}{2}\rho v^3 A$.
    * Power $\propto$ A, Power $\propto v^3$.
  - $\eta = C_p = \dot{W}/\dot{W}_{\text{avail}}$.
    * Show with momentum balance and B.E. that $C_{p,\text{max}} = 16/27 = 0.5926$.
      · This is the best possible, and the best in practice is around 0.45.
- Scaling laws are similiar as for pumps: C_H, C_Q, C_p, η, but use C_p, not C_Q as the independent parameter.
- Choose turbine type based on the Turbine specific speed N_{st}.
  - Impulse for $N_{st} < 0.3$
  - Francis for $N_{st} = 0.3 - 2$
  - Kaplan for $N_{st} > 2$
  - CAREFUL OF THE UNITS

Lecture 32 - Turbines.

- Pumps → add mechanical energy to increase fluid head
- Turbines → Extract mechanical energy via fluid head.

- Types

  Hydraulic
  Wind
  Steam
  Gas

  Turbines typically more efficient than Pumps
  - Larger → less visc effects (higher Re)
  - Less separation (pressure Drops)
  - Lower speed → lower friction
  - narrower op. range → more specific Design.

- Turbines are "like" inverse pumps.
- Some machines can op. as a pump or a turbine.

2 Types

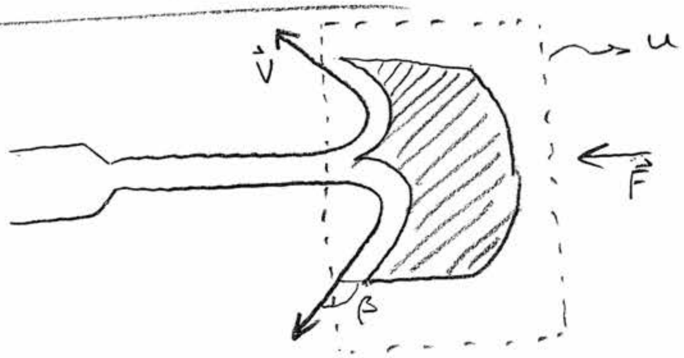
- Positive Displacement
  - mostly used for flow measurement, not power prod.
- Dynamic
  - used for flow and power.
  - pump → impeller
  - turbine → Runner.

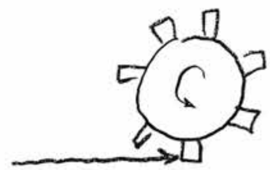
- 2 types -
  1. Impulse
  2. Reaction.

Impulse → Pelton wheel.
- High Head, lower flow.
- Fluid sent through Nozzle → P → KE.
- Nozzle jet Deflected in a bucket causing the wheel to turn → produce power.
- Flow is split, redirected.

→

Pelton wheel Analysis





- $u = \omega r$
- Groove in bucket to allow passage of jet.

Mom. Balance: Control volume around bucket.

$$\vec{F} = (\dot{m} V)_{out} - (\dot{m} V)_{in}$$

x-momentum

$$V_{in} = V_j - u$$

$$V_{out} = V_{in} \cos\beta = (V_j - u)\cos\beta$$

$$\dot{m}_j = \rho A V_j \rightarrow A = \dot{m}_j / \rho V_j$$

$$\dot{m}_r = \rho A (V_j - u)$$

$$\rightarrow \dot{m}_r = \dot{m}_j \left(1 - \frac{u}{V_j}\right)$$

Insert

$$-F = \dot{m}_j \left(1 - \frac{u}{V_j}\right)(V_j - u)(\cos\beta - 1)$$

* $$F = \dot{m}_j \left(1 - \frac{u}{V_j}\right)(V_j - u)(1 - \cos\beta)$$

* $$\dot{W} = F u = \dot{m}_j u \left(1 - \frac{u}{V_j}\right)(V_j - u)(1 - \cos\beta)$$

Optimal β: $\frac{d\dot{W}}{d\beta} = 0 = \sin\beta \longrightarrow \beta = 0°$ or $\boxed{\beta = 180°}$

- in practice $\beta \sim 160°$ otherwise hit back of bucket.
- this is same result as in mom Balance.

highest force when Deflected 180°

Optimal u:

$$\frac{d\dot{W}}{du} = 0 = \dot{m}_J(1-\cos\beta)\left[V_J - 4u + 3\frac{u^2}{V_J}\right]$$

$$\frac{3}{V_J}u^2 - 4u + V_J = 0 \longrightarrow \frac{4 \pm \sqrt{16-12}}{6/V_J} = V_J\left(\frac{4 \pm 2}{6}\right)$$

$u = V_J$ (trivial) or $\boxed{u = \frac{V_J}{3}}$

- Note, book wrong → $u = \frac{V_J}{2}$

- η up to 90%

Reaction Turbines

Like pumps - centrifugal, mixed flow, axial.

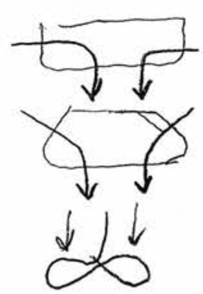
2 Types

Francis

Kaplan

Francis → radial flow
→ mixed flow

Kaplan → Axial flow (propeller w/ variable pitch)



med Head
med flow

low head
high flow

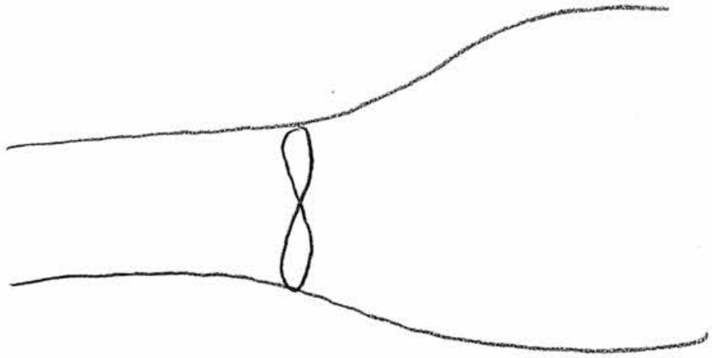
Eff: $\eta_{turb} = \frac{1}{\eta_{pump}} = \frac{bhp}{\rho g H Q}$

- Turbines can be <u>very</u> big.

Gas turbines / Steam

- multi-stage.
- Steam
- Power
- propulsion
- axial flow.

Wind Turbines.



- $\dot{W}_{avail}$ = KE × flow rate

$$= \frac{1}{2} V^2 \dot{m} = \frac{1}{2} \rho V^3 A$$

- Power $\propto A$
  $\propto V^3$

$$\frac{\dot{W}}{A} = \frac{1}{2} \rho V^3 \cdot K$$

100	W/m^2	~~[illegible]~~
400		Okay
700		Great

- $\eta = C_P = \dfrac{\dot{W}}{\frac{1}{2} \rho V^3 A}$

- Can show w/ Mom Bal / B.E. (see pg 828-829)
  → That $C_{P,max} = \frac{16}{27} = \underline{\underline{0.5926}}$ → best possible!

  - Best in practice $\sim \underline{\underline{0.45}}$

Scaling laws

Like pumps : C_H, C_Q, C_P, η

But use C_P not C_Q as indep parameter.

$$C_H = C_H(C_P)$$
$$C_Q = C_Q(C_P)$$ again, neglecting Re, $\frac{\epsilon}{D}$ effects.
$$\eta = C_\eta(C_P)$$

Choosing Pump & Turbine Types

Specific speed

Pumps

$\frac{\text{Flow}}{\text{Head}}$: ratio w/o D

$$N_{sp} = \frac{C_Q^{1/2}}{C_H^{3/4}} = \frac{Q^{1/2}}{\omega^{1/2} D^{3/2}} \cdot \frac{\omega^{3/2} D^{3/2}}{g^{3/4} H^{3/4}} = \frac{\omega Q^{1/2}}{(gH)^{3/4}}$$

- each pump has BEP at Diff. N_s
- Plot η_{max} vs N_{sp}

use to choose pump type.

Cent	$N_{sp} < 1.5$
mixed	N_{sp} 1.5 - 3.5
axial	$N_{sp} > 3.5$

Turbines

$$N_{st} = \frac{\omega (bhp)^{1/2}}{\rho^{1/2} (gH)^{5/4}}$$

Impulse	$N_{st} < 0.3$
Francis	N_{st} 0.3 - 2
Kaplan	$N_{st} > 2$

U.S. Pumps

$$\rightarrow \frac{n(rpm)\left[Q(gal/min)\right]^{1/2}}{H\ (ft)}$$

U.S. turb

$$\rightarrow \frac{n(rpm)\left(bhp\ (hp)\right)^{1/2}}{(H, ft)^{5/4}}$$

European version too