09-Off-Grid Micro Hydro Power Systems

Off-Grid Electrical Systems in Developing Countries, 2nd Edition

Chapter 9

Preface

- These lectures slides are intended to accompany the textbook *Off-Grid Electrical Systems in Developing Countries, 2nd Edition, 2025* written by Dr. Henry Louie and published by SpringerNature
- Additional content, explanations, derivations, examples, problems, errata, and other materials are found in the book and on www.drhenrylouie.com
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Learning Outcomes

At the end of this lecture, you will be able to:

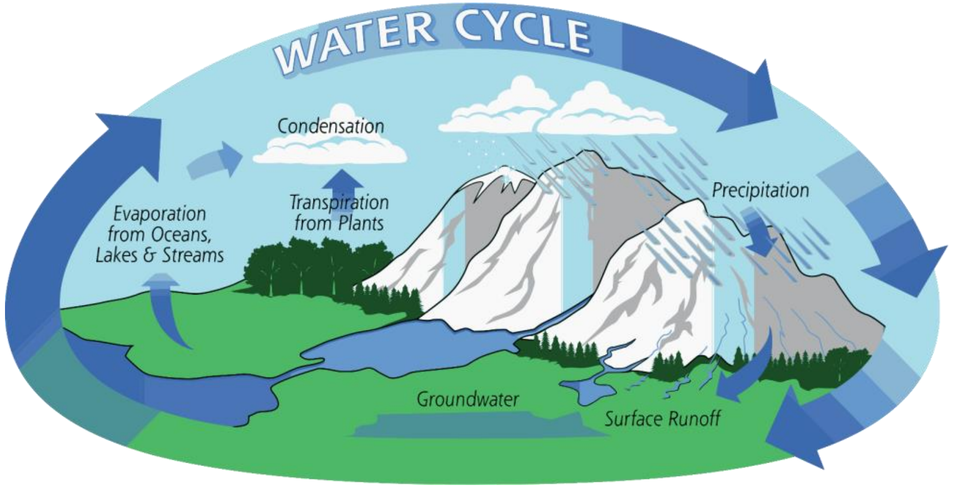
- ✓Describe the use of micro hydro power (MHP) in off-grid electrification, emphasizing the key technical, economic, environmental, and social considerations
- ✓Identify the components of an MHP system
- ✓Explain the core principles of MHP operation using appropriate mathematical models
- ✓Select an appropriate hydro turbine for a given hydro resource and electrical generation requirement
- ✓Produce a preliminary design of a Pelton turbine for an MHP system

Introduction

- Hydropower is a mature energy conversion technology and widely used in off-grid electrification
- Micro hydro power (MHP) capacity typically: up to 100 kW
  - most do not use dams
- MHP can have the lowest energy costs of all off-grid generation sources
- Requires adequate water resource and terrain to be feasible

Hydro Resources

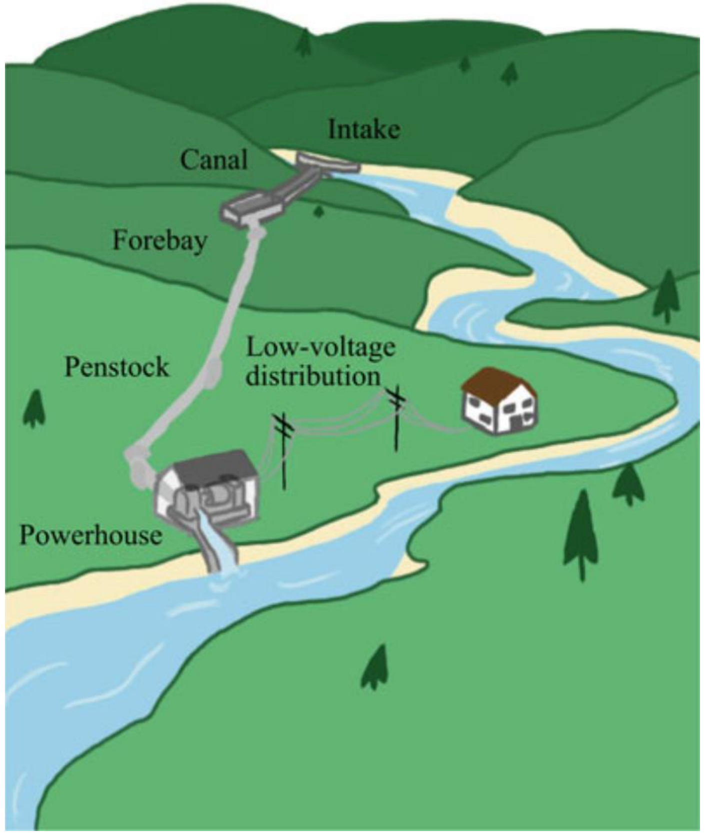
- Hydroelectric generation is the conversion of the energy in water to electrical energy
- Energy flow:
  - solar energy evaporates water to create water vapor
  - water vapor rises in the atmosphere
  - as it rises, it gains potential energy
  - when the water vapor condenses, it falls to earth
  - the water flows downhill back to the ocean



(source NASA)

Micro Hydro Power (MHP)

- Turbines convert energy in water into mechanical energy to power a hydro turbine
- Consistent power can be generated
- Can be AC-coupled or DC-coupled
- Civil works are required



Hydro Resource

- Power potential of a hydro resource depends on:
  - head (m)
  - flow rate (m^3/s)
  - conveyance system loss estimate
- Desirable characteristics
  - steep surrounding terrain (reduces penstock length and losses)
  - water intake at high elevation compared to powerhouse location
  - consistent, predictable seasonal flow

Hydro Resource

- From Bernoulli, the energy in a volume of water depends on its
  - kinetic energy
  - potential energy
  - internal energy
- Energy from pressure and velocity often ignored

$$\frac{1}{2}\rho_{wa}v_{wa}^2 + \rho_{wa}gz + p_{wa} = K$$

ρ_{wa}: density of water, 1000 kg/m^3
v_{wa}: velocity of water, m/s
g: gravitational constant, 9.8 m/s^2
z: elevation, m
P_{wa}: pressure, Pa
K: constant, J/m^3

Bernoulli's Equation

$$\underbrace{\frac{1}{2}\rho_{wa}v_{wa}^{2}}_{\text{kinetic energy}} + \overbrace{\rho_{wa}gz}^{\text{potential energy}} + \underbrace{p_{wa}}_{\text{internal energy}} = K$$

Bernoulli's Equation

What happens if water is flowing through a pipe and then a valve is closed so that the velocity suddenly drops to zero?

$$\frac{1}{2}\rho_{wa}v_{wa}^{2} + \rho_{wa}gz + p_{wa} = K$$

pressure can rapidly increase
("water hammer" effect)

Total Head

Re-writing Bernoulli's equation by dividing both sides by the water density, ρ_{wa}, and the gravitational constant, g:

$$\frac{1}{2}\rho_{wa}v_{wa}^{2} + \rho_{wa}gz + p_{wa} = K$$

all have units of meters

$$\underbrace{\frac{1}{2g}v_{\text{wa}}^{2}}_{\text{velocity head}} + \underbrace{z}_{\text{elevation head}} + \underbrace{\frac{p_{\text{wa}}}{\rho_{\text{wa}}g}}_{\text{pressure head}} = H_{\text{t}} \longleftarrow \text{total head}$$

Total Head

Total Head: allows the energy density of a hydro resource to be expressed by one value (total head), with more familiar units (m)

$$\frac{1}{2g}v_{\mathrm{wa}}^{2}+z+\frac{p_{\mathrm{wa}}}{\rho_{\mathrm{wa}}g}=H_{\mathrm{t}}$$

Total Head

The <u>total</u> energy in a volume of water, in joules, is related to total head as:

$$E_{\mathrm{wa,total}} = g \times H_{\mathrm{t}} \times \rho_{\mathrm{wa}} \times V_{\mathrm{wa}}$$

in m^3

Total Head

- The total energy is the same as the potential energy of a mass of water with density ρ_{wa} and volume V_{wa} at an elevation of H_t

$$E_{wa,total} = g \times H_t \times \rho_{wa} \times V_{wa}$$

recall: potential energy = *m* x *g* x *h*

- We can conceptually replace water with a certain velocity, elevation, and pressure, with an equivalent mass (or volume) of water with no velocity, no pressure, and at an elevation of H_t

Example 9.1

Compute the total head of two cubic meters of water whose velocity is 1 m/s and is located 38 meters above the reference plane. The water is exposed to atmospheric pressure (101.325 kPa). Compute the total head.

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note that the total head is greater than the height of the water above the reference plane

$$H_t = \frac{1}{2g} v_{wa}^2 + z + \frac{p_{wa}}{\rho_{wa} g}$$

$$H_t = \frac{1}{2 \times 9.81} 1^2 + 38 + \frac{101{,}325}{1000 \times 9.8} = 0.05 + 38 + 10.33 = 48.39 \text{ m}$$

most (38 m) of the total head comes from the elevation head

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$$E_{\mathrm{wa,total}} = \rho_{\mathrm{wa}} \times V_{\mathrm{wa}} \times g \times H_{\mathrm{t}} = 1000 \times 2 \times 9.81 \times 48.38 = 0.949 \text{ MJ}$$

this is the same value as if we applied Bernoulli's equation

Effective Head

- Effective head: head available to the hydro turbine for energy conversion
- Effective head accounts for losses

Effective Head < Total Head

Effective Head and Total Head

- Difference between total head and effective head is due to:
  - conveyance losses (friction, etc.) in the penstock—these losses are expressed as a reduction of the total head by H_f
  - velocity head is assumed to be zero
  - pressure head is zero (the turbine ultimately rejects water that is also at atmospheric pressure)
- These differences have the conceptual effect of lowering the location of the water used by the hydro turbine (and reducing its potential energy)

$$H = z - H_f = z\eta_{\text{convey}}$$

effective head is the elevation of the water minus the losses as expressed in head

Flow Rate

- Useable energy in a volume of water

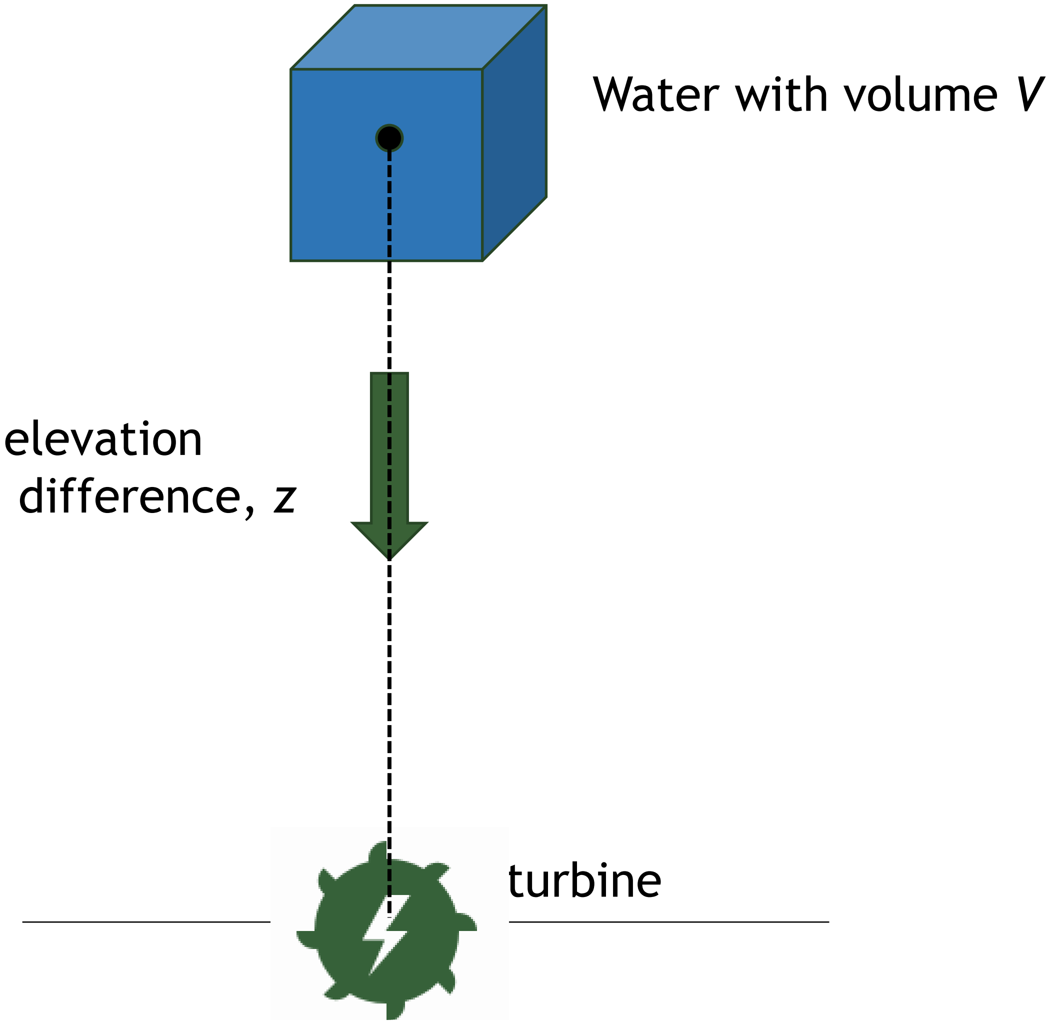
$$E_{wa} = g \times H \times m_{wa} = g \times H \times \rho_{wa} \times V$$

- Power in falling water

$$P_{wa} = \frac{dE_{wa}}{dt} = \rho_{wa} \times g \times H \times Q$$

g: gravitational constant, 9.8 m/s^2
H: effective head, m
m_{wa}: mass of water, kg
V: volume of water, m^3
ρ_{wa}: density of water, 1000 kg/m^3
Q: water flow rate, m^3/s

note: 1 m^3/s = 1000 liter/s



Power Extraction

The turbine can only extract a portion of the power in the water

$$P_{\text{d,turbine}} = P_{\text{wa}} - P_{\text{outlet}} = \eta_{\text{turbine}} P_{\text{wa}}$$

η_{turbine}: efficiency of the turbine
$P_{\text{d,turbine}}$: mechanical power developed by the turbine (W)
P_{outlet}: power of the water at the turbine’s outlet (W)
E_{turbine}: efficiency of the turbine

Exercise

The water resource for a MHP scheme is 38 m above the hydro turbine. The flow rate is 0.005 m^3/s (5 liters per second). Assume the conveyance system efficiency is 90%. Compute power available to the input of the turbine.

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The effective head is

$$H = z\eta_{\text{convey}} = 38\ \text{m} \times 0.90 = 34.2\ \text{m}$$

Exercise

The water resource for a MHP scheme is 38 m above the hydro turbine. The flow rate is 0.005 m^3/s (5 liters per second). Assume the conveyance system efficiency is 90%. Compute power available to the input of the turbine.

The power at the inlet to the turbine is

$$P_{wa} = \rho \times g \times H \times Q = 1000 \times 9.8 \times 34.2 \times 0.005 = 1675 \text{ W}$$

Exercise

The water resource for a MHP scheme is 38 m above the hydro turbine. The flow rate is 0.005 m^3/s (5 liters per second). Assume the conveyance system efficiency is 90%. Compute power available to the input of the turbine.

The power extracted at the turbine is

$$P_{\text{turbine}} = \eta_{\text{turbine}} P_{\text{wa}} = 0.85 \times 1675 = 1424 \text{ W}$$

Hydro Turbines

- Hydro turbines: extract energy from water and use it to rotate a shaft (coupled to a generator)
- Hydro turbines are usually custom made for specific head and flow requirements

MHP Turbine Types

Pelton

(*source: H. Louie*)

Crossflow

(*source: Canyon Industries*)

Francis

(*source: H. Louie*)

Turgo

(*source: Canyon Industries*)

Turbine Selection

Most water resources for MHP are high head or medium head, which require less flow

High Head	Medium Head	Low Head
Pelton	Crossflow	Crossflow
Pelton (Multi-jet)	Turgo	Propeller
Turgo	Pelton (Multi-jet), Francis	Kaplan

(*source: H. Louie*)

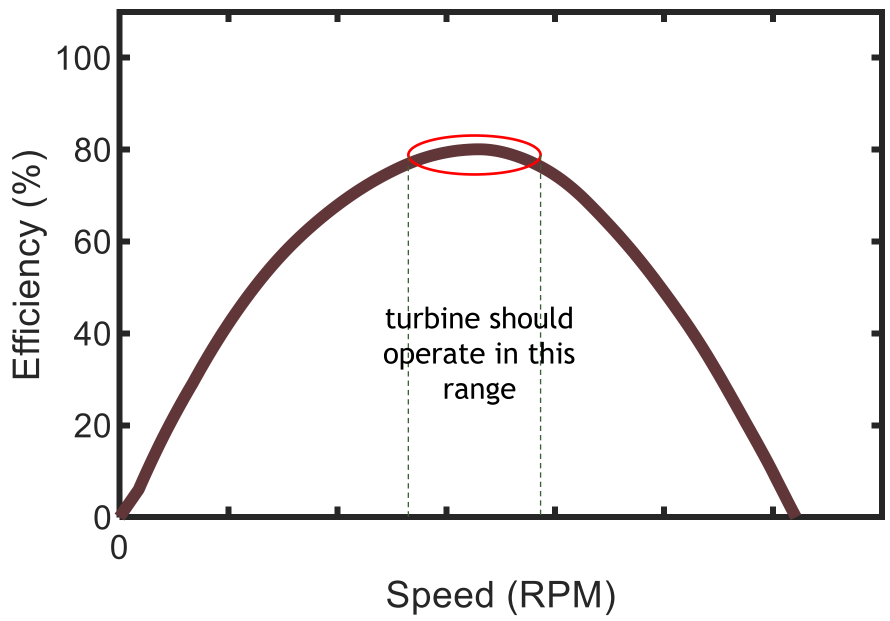
Kaplan turbines not common in MHP

Turbine Selection

Select hydro turbine type that will operate most efficiently given the power and rotational speed requirements, and the water resource speed and head

- Turbine Application Chart
- calculated using "specific speed"

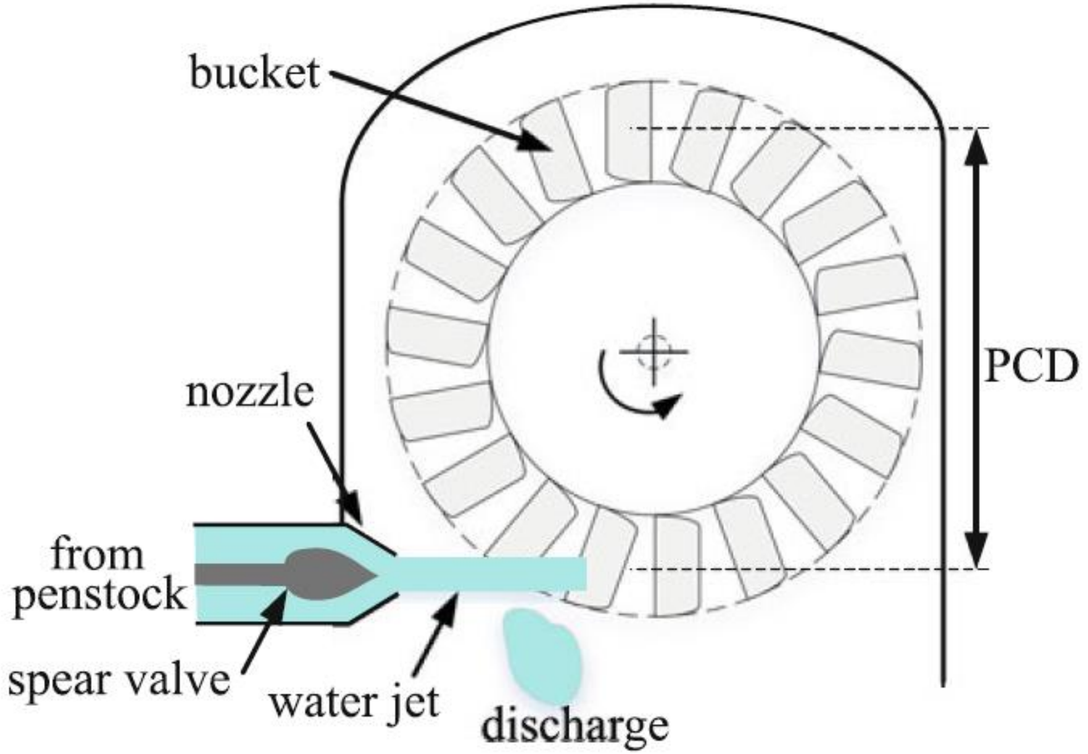
Illustrative efficiency curve for Pelton Turbine



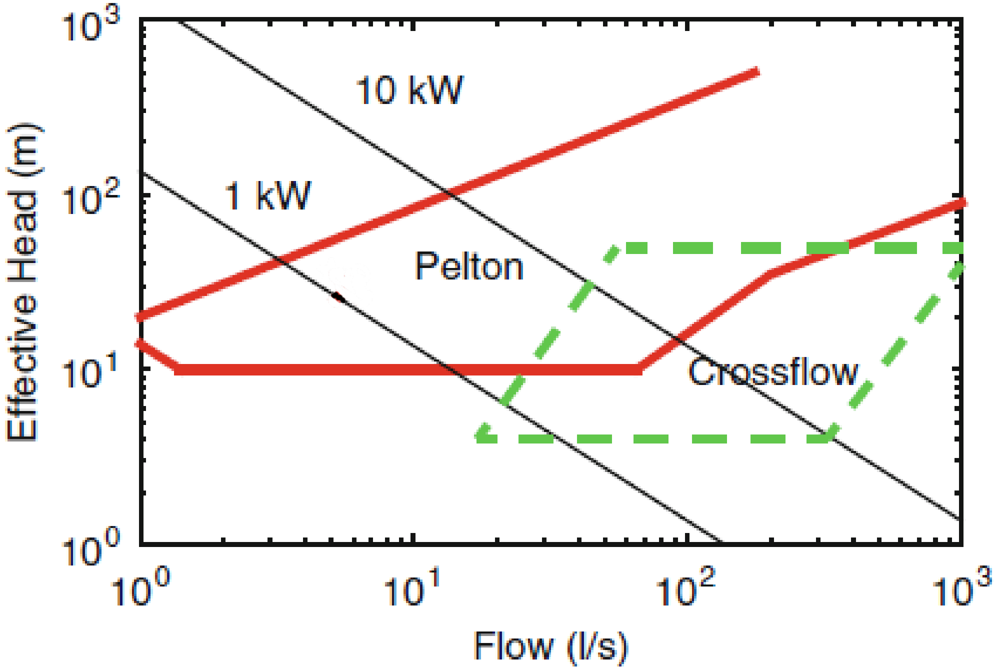
Speed Matters

- Velocity of water jet depends on head
- Efficiency is maximized when water jet speed is 1/2 the tangential speed of the bucket
- Bucket must rotate at certain RPM to produce desired voltage frequency
- Mismatch of resource and turbine lowers efficiency

Pelton Turbine



Turbine Application Chart

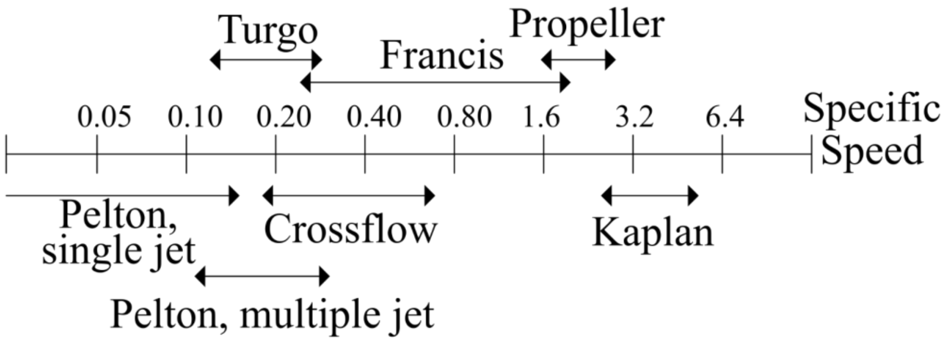


Specific Speed (Dimensionless)

$$S = \frac{\omega_m \sqrt{Q}}{(gH)^{3/4}} = \frac{\omega_m \sqrt{P_{d,turbine} / \rho_{wa}}}{(gH)^{5/4}}$$

ω_m: rotational speed of turbine, rad/s
g: gravitational constant, m/s^2
H: effective head, m
Q: water flow rate, m^3/s

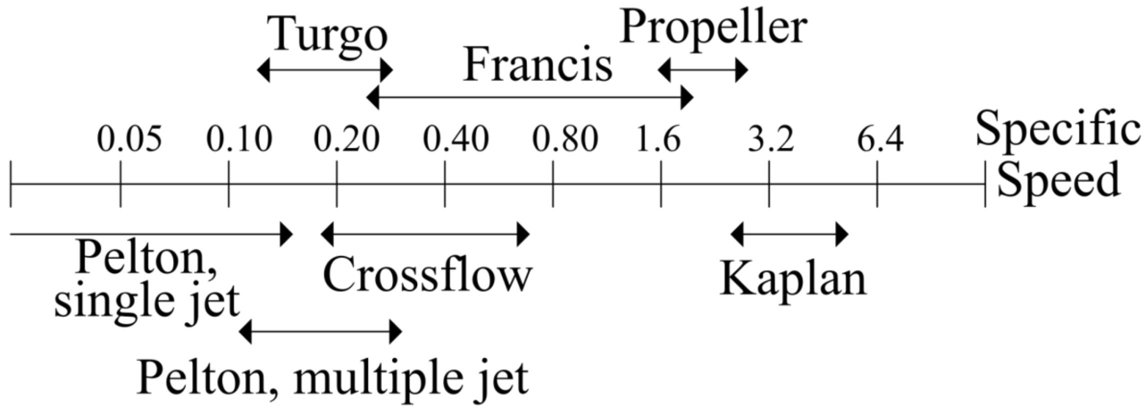
note: scale is non-linear



caution: several other "dimensioned" specific speeds are used and reported by turbine manufacturers

Specific Speed

For many MHP systems, the power developed, rotational speed, and head are such that Pelton, Turgo, or crossflow turbines should be selected



Example 9.3

Compute the dimensionless specific speed for a water resource with an effective head of 30 m. Assume the turbine will rotate 1500 RPM with a developed mechanical power of 1.25 kW

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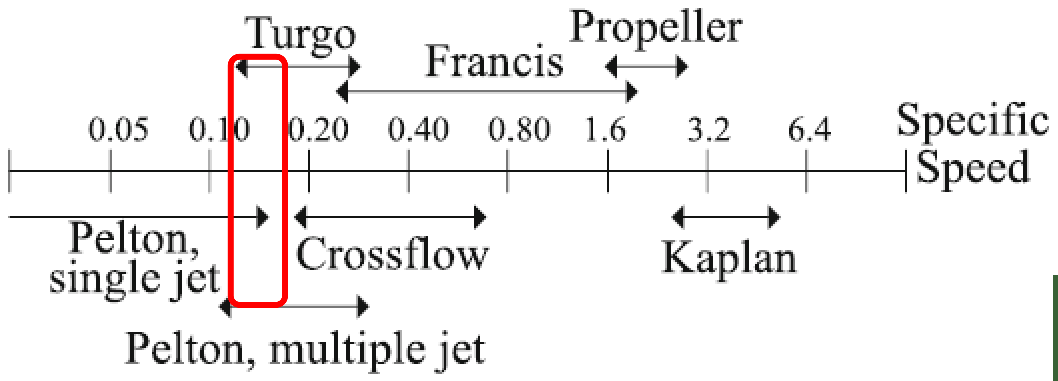
Compute the dimensionless specific speed for a water resource with an effective head of 30 m. Assume the turbine will rotate 1500 RPM with a developed mechanical power of 1.25 kW

$$S = \frac{\omega_m \sqrt{P_{\text{d,turbine}} / \rho_{\text{wa}}}}{(gH)^{5/4}} = \frac{\frac{2\pi}{60} \times 1500\sqrt{1250 / 1000}}{(9.8 \times 30)^{5/4}} = 0.144$$



we see that a Pelton or Turgo turbine would be suitable for this application

Exercise

Compute the dimensionless specific speed for a water resource with an effective head of 10 m. Assume the turbine will rotate 1500 RPM with a developed mechanical power of 1.25 kW. What turbine(s) would be suitable for this application?

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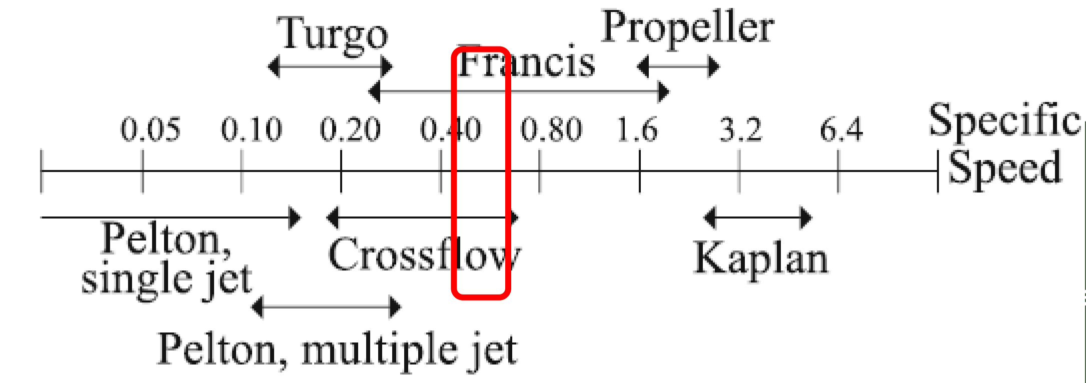
Compute the dimensionless specific speed for a water resource with an effective head of 10 m. Assume the turbine will rotate 1500 RPM with a developed mechanical power of 1.25 kW. What turbine(s) would be suitable for this application?

$$S = \frac{\omega_m \sqrt{P_{\text{d,turbine}} / \rho_{\text{wa}}}}{(gH)^{5/4}} = \frac{\frac{2\pi}{60} \times 1500\sqrt{1250/1000}}{(9.8 \times 10)^{5/4}} = 0.568$$

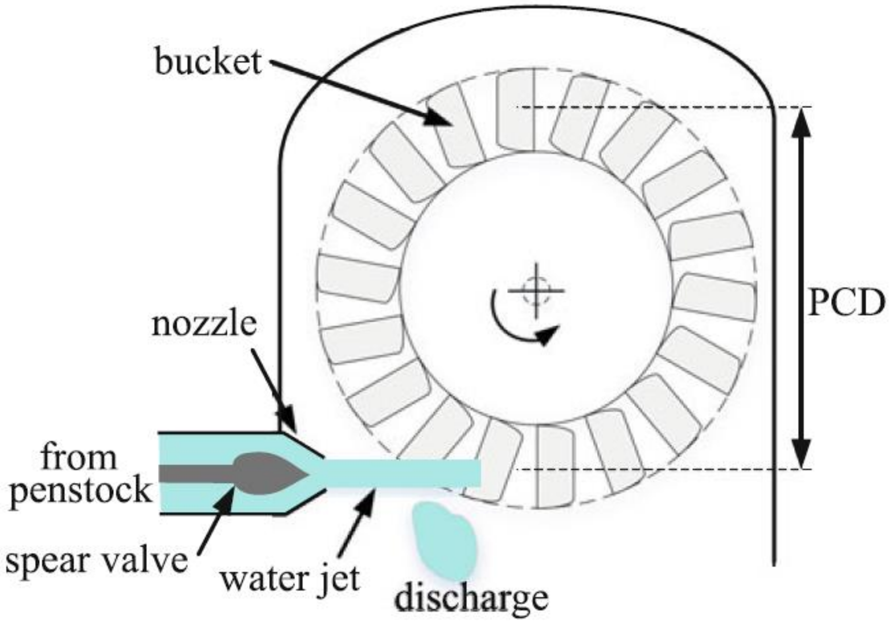
this "low head" resource would require a Francis or cross flow turbine



Turbine Design

We will consider the design of a single-nozzle pelton turbine to see how the characteristics of the hydro resource interplay with our design decisions

(*courtesy: H. Louie*)



PCD: Pitch Circle Diameter

Pelton Turbine

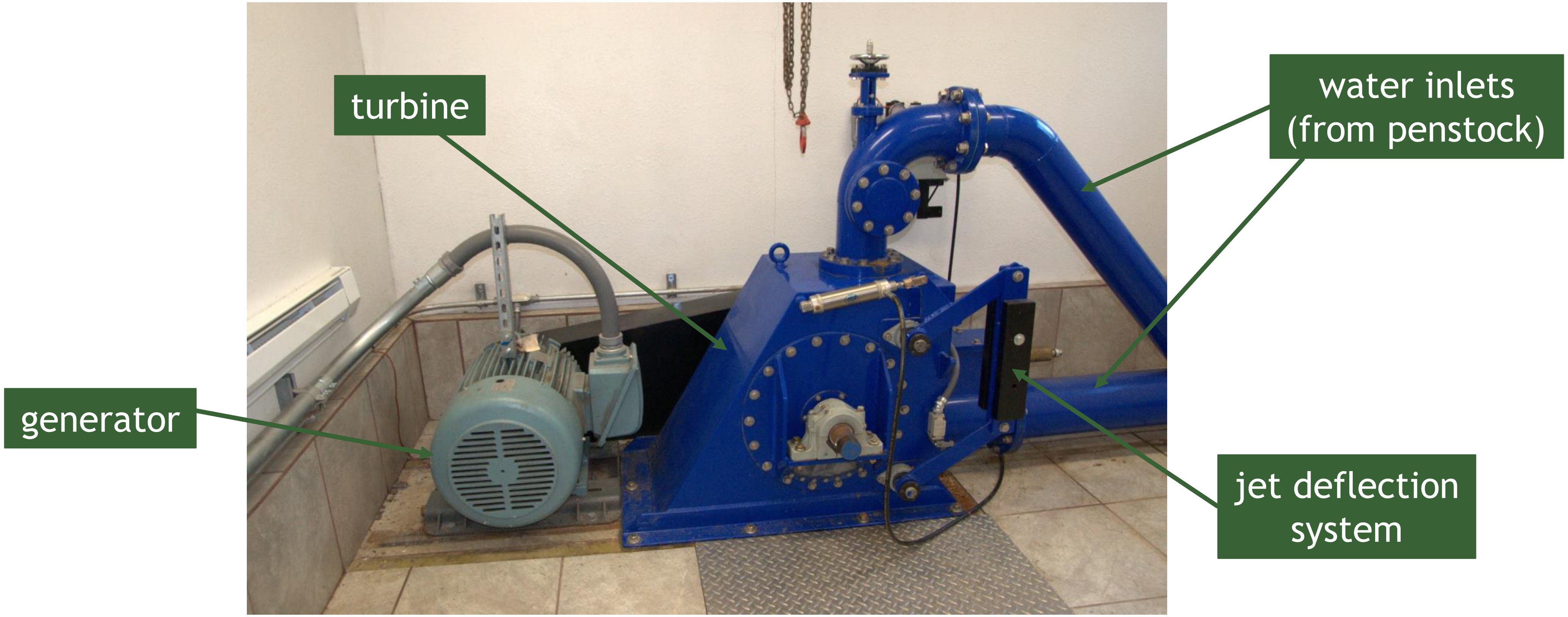
small four-nozzle Pelton turbine

(*courtesy: E. Youngren*)

large Pelton turbine

(*courtesy: H. Louie*)

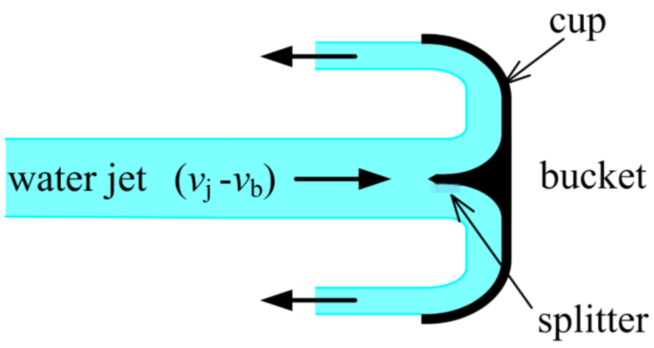
Two-Nozzle Pelton Turbine System



(*courtesy: H. Louie*)

Pelton Turbine

- Nozzle aims water at the splitter in turbine's buckets
  - v_j: water jet velocity (m/s)
  - v_b: tangential bucket velocity (m/s)
- What should the relationship between v_j and v_b be so that the maximum amount of kinetic energy is transferred to the bucket?



face of bucket with splitter in the middle

(*courtesy: H. Louie*)

Pelton Turbine Design

- Design the system so that the force on each bucket is maximized
- Note that $(v_j - v_b)$ is the relative velocity, $v_{relative}$ between the bucket and jet
- Force is equal to rate of change of momentum (M)

$$F = \frac{dM}{dt} = 2\rho_{wa} Q \left(v_j - v_b\right)$$

factor of two is a result of the change in direction of the water as it flows around the bucket

Pelton Turbine Design

- The power developed by the turbine is found by recognizing that power = force x velocity

$$P_{\text{d,turbine}} = 2\rho_{\text{wa}} Q \left(v_{\text{j}} - v_{\text{b}}\right) v_{\text{b}}$$

- This is maximized when

$$\frac{dP_{\text{d,turbine}}}{dv_{\text{b}}} = 2\rho_{\text{wa}} Q v_{\text{j}} - 4\rho_{\text{wa}} Q v_{\text{b}} = 0$$

$$2v_{\text{j}} - 4v_{\text{b}} = 0$$

$$\frac{v_{\text{b}}}{v_{\text{j}}} = 0.5 = y$$

optimal speed of a Pelton turbine is when the velocity of the jet of water is twice the velocity of the bucket

"*y*" is known as the "speed ratio"

Pelton Turbine Design

- Maximum power developed by the turbine is

$$P^{*}_{\mathrm{d,turbine}} = \frac{1}{2}\rho_{\mathrm{wa}} Q v_{\mathrm{j}}^{2}$$

denotes maximum

- If the speed of the jet is not equal to twice the speed of the bucket, the developed power is not maximum and we conclude the turbine is not operated efficiently

Developed Power

Note that if we want to increase the power developed by the turbine, we can either increase the flow rate, or increase the velocity of the water jet

- But, keep in mind that to keep the turbine operating at an optimal speed, if we increase the water jet velocity we must also increase the bucket speed

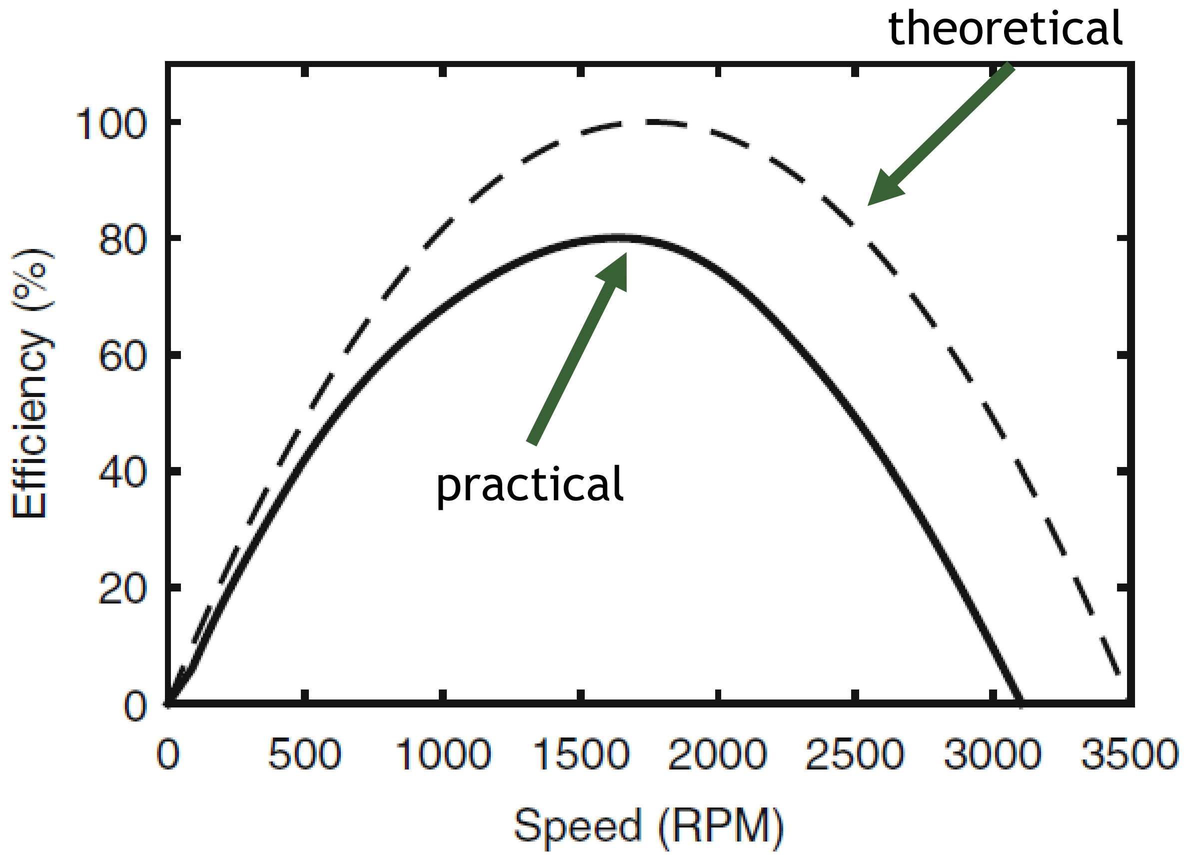
$$P^*_{\mathrm{d,turbine}} = \frac{1}{2}\rho_{\mathrm{wa}} Q v_{\mathrm{j}}^2$$

Pelton Turbine Efficiency

- Efficiency is

$$\eta_{\text{turbine}} = \frac{P_{\text{d,turbine}}}{P_{\text{wa}}} \times 100\%$$

- Theoretical efficiency is 100%
- Actual efficiency is ~50-85%, with maximum efficiency when *y* is around 0.46



Pelton Turbine Design

- We know we should design our turbine so that the tangential bucket speed is half the speed of the incoming jet of water
- How do we achieve this?
- Consider the velocity of the jet of water

$$mgH = \frac{1}{2} m v_j^2$$

assuming lossless nozzle, the potential energy of the water equals the kinetic energy of the jet

$$v_j = \sqrt{2gH}$$

jet velocity depends on the effective head of the resource

Speed Equation

Rotational speed of the turbine is:

$$v_b = \frac{d_{PCD}}{2}\omega_m$$

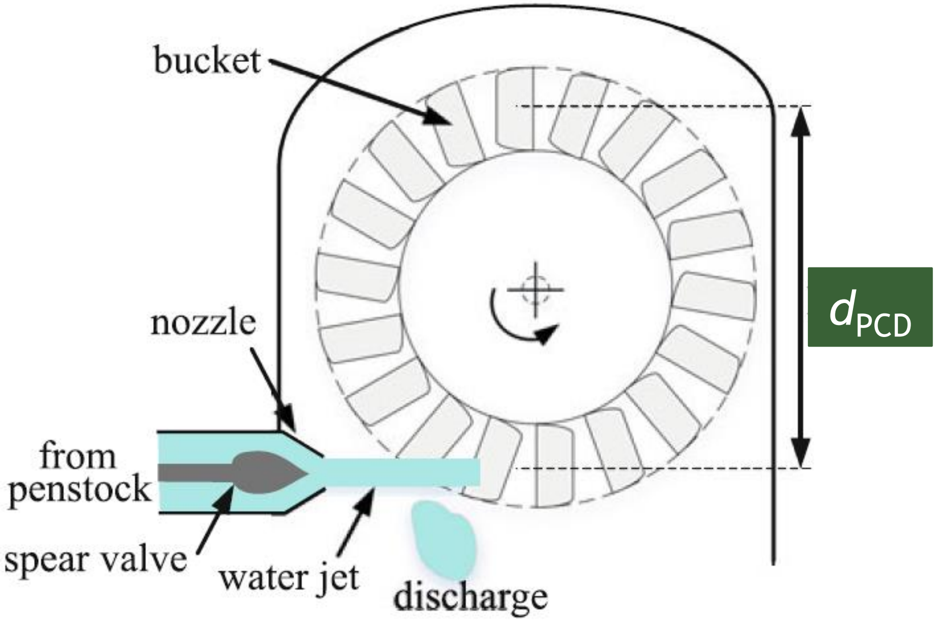
tangential velocity = radius x angular velocity

$$\omega_m = \frac{2v_b}{d_{PCD}}$$

$$N_m = \omega_m \frac{60}{2\pi} = \frac{2v_b \times 60}{d_{PCD} \times 2\pi} = \frac{y \times v_j \times 60}{\pi d_{PCD}}$$

"speed equation"

N_m: speed, in RPM



Speed Equation

- In terms of the effective head:

$$N_{\mathrm{m}} = \frac{y \times v_{\mathrm{j}} \times 60}{\pi d_{\mathrm{PCD}}} = \frac{y \times \sqrt{2gH} \times 60}{\pi d_{\mathrm{PCD}}}$$

recall that: $v_{\mathrm{j}} = \sqrt{2gH}$

- This equation that relates the rotational speed of the turbine, the head of the resource, and the PCD diameter of the turbine

Pelton Turbine Design

- For practical reasons, we usually design the turbine such that

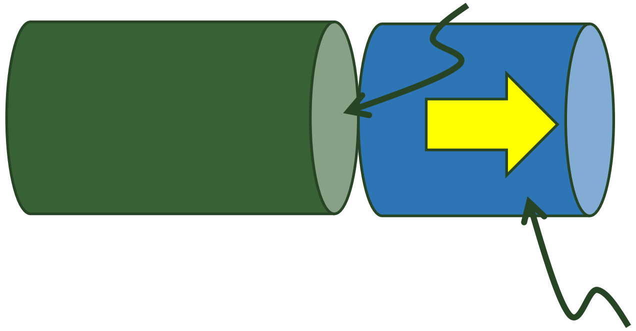
$$d_{\text{PCD}} \geq \frac{d_{\text{jet}}}{0.11}$$

- In other words, the diameter of the water jet, d_{jet}, cannot be made arbitrarily large. It should be no more than about 11% of the turbine's PCD

Pelton Turbine Design

- How do we determine the diameter of the water jet?
- Start with relating flow rate to water jet velocity:

$$Q = A_{noz} v_{jet} = A_{noz}\sqrt{2gH}$$



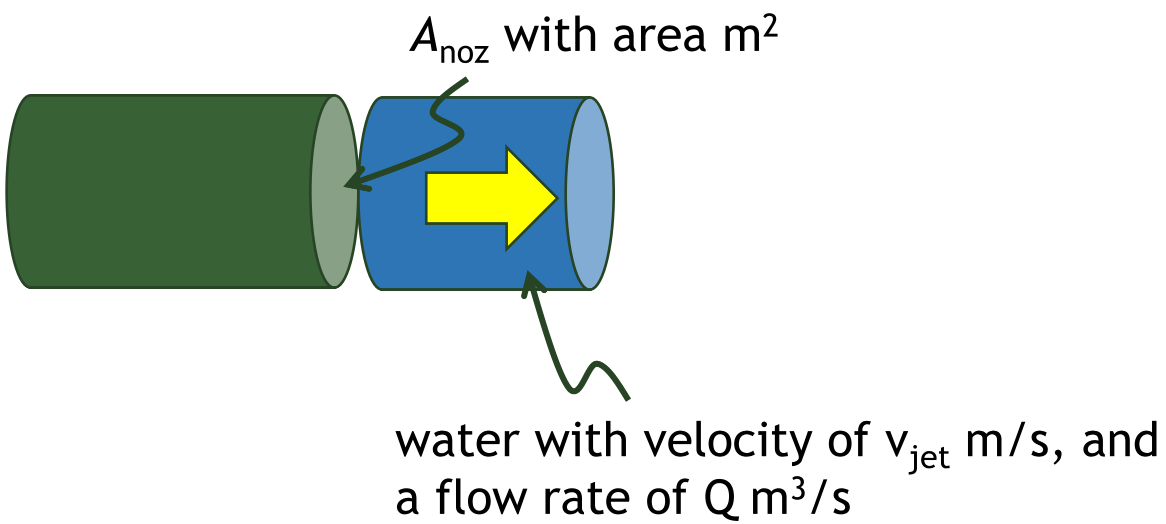
Nozzle Diameter

Relating area to diameter:

$$Q = A_{noz} v_{jet} = A_{noz}\sqrt{2gH}$$

$$Q = \frac{\pi d_{jet}^2}{4}\sqrt{2gH}$$

$$d_{jet} = \left(\frac{4Q}{\pi\sqrt{2gH}}\right)^{0.5}$$



Exercise

To achieve a higher flow rate, the diameter of the water jet must (assuming everything remains the same):

A. Increase
B. Decrease
C. The diameter is not affected by flow rate

$$d_{\text{jet}} = \left(\frac{4Q}{\pi\sqrt{2gH}} \right)^{0.5}$$

Exercise

To achieve a higher flow rate, the diameter of the water jet must (assuming everything remains the same):

A. Increase
B. Decrease
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$$d_{\text{jet}} = \left(\frac{4Q}{\pi\sqrt{2gH}} \right)^{0.5}$$

Exercise

If the head of the system is increased, but the flow rate remains the same, the diameter of the jet must

A. Increase
B. Decrease
C. The diameter of the jet is not affected by the head

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A. Increase
B. Decrease
C. The diameter of the jet is not affected by the head

$$d_{\text{jet}} = \left(\frac{4Q}{\pi \sqrt{2gH}} \right)^{0.5}$$

Exercise

- Assume a Pelton turbine is directly coupled to a four-pole synchronous generator. The generator is to produce 50 Hz AC. The required power is 10 kW. The generator is 90% efficient. The head of the hydro resource is 70 m. Assume the maximum efficiency of Pelton turbine (100%) is achieved when y =0.50.

- Determine the PCD of the turbine, the diameter of the jet, and the required flow rate.

Exercise

- Start by determining the input power required by the turbine:

$$P_{\text{d,turbine}} = 10 \times \frac{1}{0.90} = 11.11 \text{ kW}$$

$$P_{\text{wa}} = \frac{P_{\text{d,turbine}}}{\eta_{\text{turbine}}} = 11.11 \text{ kW}$$

- Next, compute the corresponding flow rate

$$P_{\text{wa}} = \rho_{\text{wa}} \times g \times H \times Q$$

$$Q = \frac{P_{\text{wa}}}{\rho_{\text{wa}} \times g \times H} = \frac{11{,}111}{1000 \times 9.8 \times 70} = 0.0162 \text{ m}^3 / s$$

Exercise

- Now determine the PCD from

$$N_m = \frac{y \times \sqrt{2gH} \times 60}{\pi d_{PCD}}$$

$$d_{PCD} = \frac{y \times \sqrt{2gH} \times 60}{\pi N_m} = \frac{0.5 \times \sqrt{2 \times 9.8 \times 70} \times 60}{\pi \times 1500} = 0.2359 \text{ m} \approx 9.25 \text{ inches}$$

Four-pole machine designed to output 50 Hz, so the speed is 3000/2 = 1500 RPM

Exercise

- Finally, determine the diameter of the jet

$$d_{\text{jet}} = \left(\frac{4Q}{\pi\sqrt{2gH}} \right)^{0.5} = \left(\frac{4 \times 0.0162}{\pi\sqrt{2 \times 9.81 \times 70}} \right)^{0.5} = 0.0236 \text{ m} \approx 0.93 \text{ inch}$$

- This is less than 11% of the PCD, so the design is viable

Multiple Jets

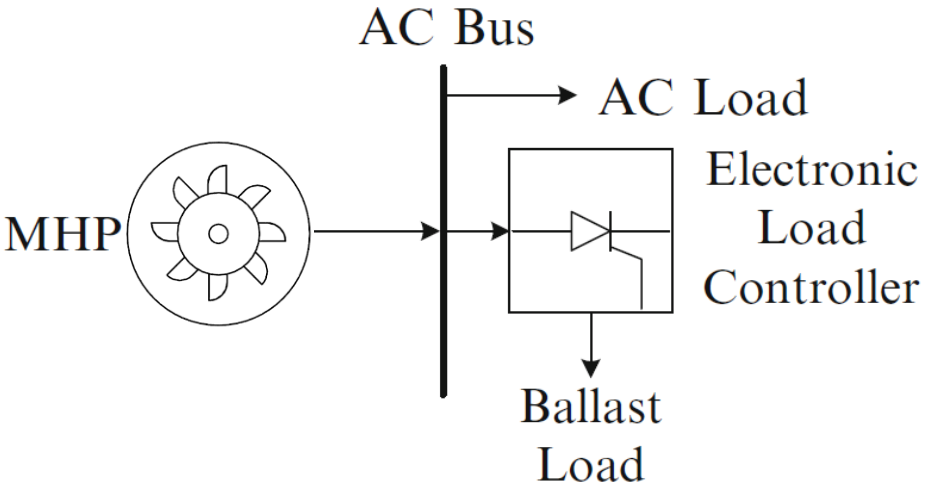
Using multiple jets allow higher rotational speeds, better flow control (nozzles can be closed individually) and reduced chance of total blockage

$$d_{\text{jet}} = \left(\frac{4Q\left(\frac{1}{b}\right)}{\pi\sqrt{2gH}} \right)^{0.5}$$

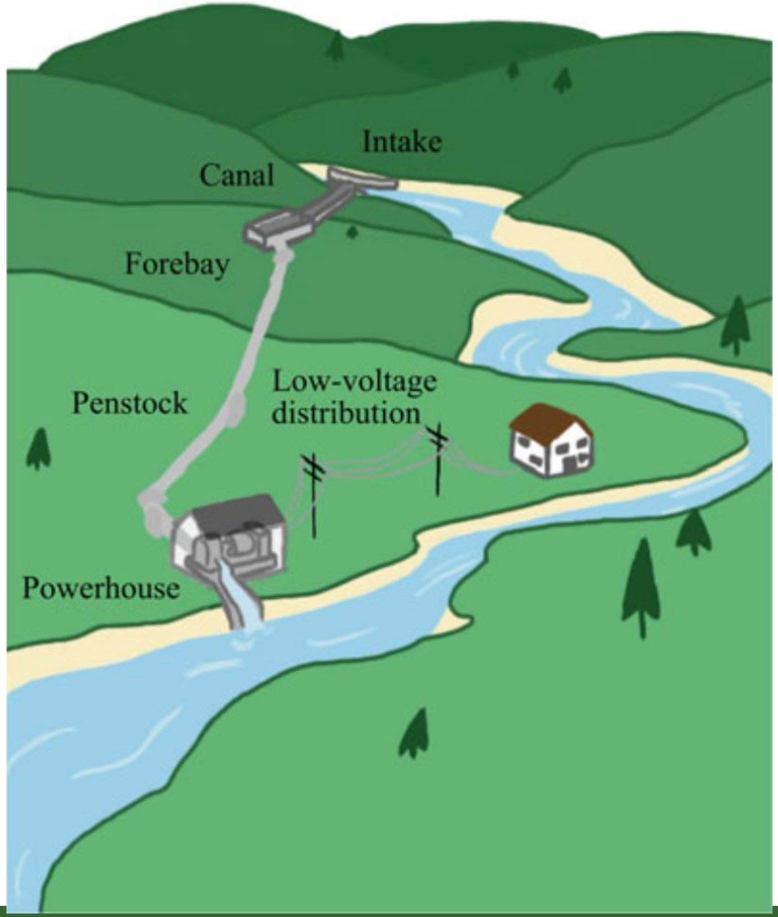
b: number of nozzles

Turbine Control

- Can be AC- or DC- coupled
- Frequency Regulation
  - Spear valve: adjust water flow to turbine
  - Electronic load controller: adjust electrical power to ballast (dummy) load to keep electrical power constant
- Voltage Regulation
  - Automatic Voltage Regulator (synchronous generator)
  - Impedance controller (self-excited induction generators)
- Do not suddenly remove load (overspeed can result)



Conveyance Systems



Water Intake

Only a portion of the stream is diverted for MHP use

(courtesy Joe Butchers)

(courtesy Joe Butchers)

(courtesy Joe Butchers)

Intake

(*courtesy: H. Louie*)

Removeable boards to clear silt/debris

(*courtesy: H. Louie*)

Water passes through grate into penstock (not visible)

Penstock

- Conveys water from intake to turbine
- Above- or below-ground pipe
- Should straight, short, and steep

(courtesy Joe Butchers)

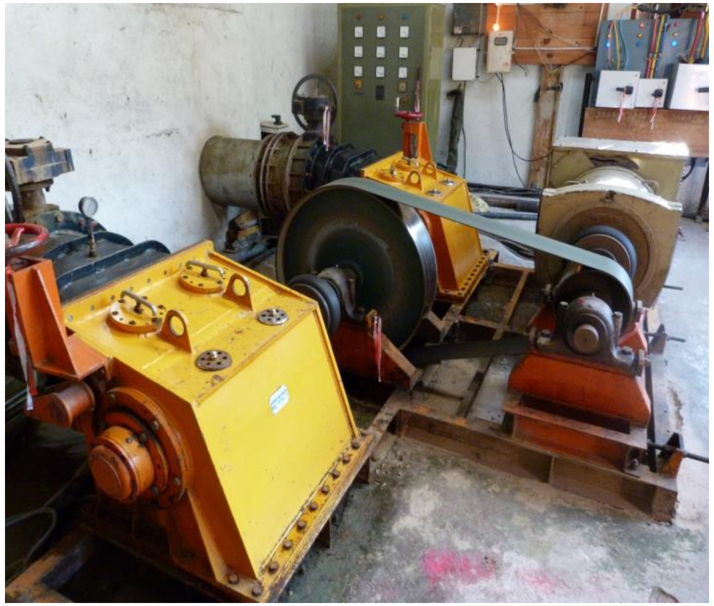
(courtesy Joe Butchers)

(courtesy Joe Butchers)

Turbine Coupled to Generator

(courtesy H. Louie)

(courtesy J. Butchers)



(courtesy J. Butchers)

MHP System Efficiency

Total efficiency depends on efficiency of individual sub-systems

$$\eta_{\text{MHP}} = \eta_{\text{intake}} \times \eta_{\text{penstock}} \times \eta_{\text{manifold}} \times \eta_{\text{nozzle}} \times \eta_{\text{runner}} \times \eta_{\text{drive}} \times \eta_{\text{gen}}$$

Economic Considerations

- Capital cost: US$1300 to US$8000/kW (including installation); conveyance system can be costly
- Fuel cost: no fuel cost (under most situations)
- Replacement cost: MHP can last decades with minimal maintenance or need for replacement
- Energy cost: can be lowest of all off-grid generation sources, US$0.30/kWh or less
- Other: mass-manufactured (inexpensive) turbines may not match hydro resource conditions

Environmental Considerations

- Resource availability: river/stream elevated above turbine location with steep surrounding terrain needed
  - Local measurements needed to assess resource
- Water use: potential to divert valuable water and affect ecosystems
- Land use: conveyance system can disrupt and block passage

Social Considerations

- Community benefit: often not practical for individual users, but low energy cost and high energy density has potential to serve many users
- Community burden: diversion of water may affect many in the community
- Other: high capital costs and specialized design of conveyance and turbine are barriers to adoption without external assistance

Other Considerations

- MHP are mature and have been used widely for off-grid systems (in areas with suitable resource)
  - body of knowledge and existing document is large
- Many stakeholders can be affected by MHP
- Greater regulatory approval and compliance may be needed

Summary

- MHP use energy in water to produce electricity
- Potential for very low-cost electricity
- Hydro turbines must match conditions of available resource (head, flow rate) and output requirements (power, frequency)
- MHP turbines include: Pelton, crossflow, turgo, francis
- Can be AC-coupled or DC-coupled