09-Micro Hydro Power Systems

Off-Grid Electrical Systems in Developing Countries

Chapter 6.3

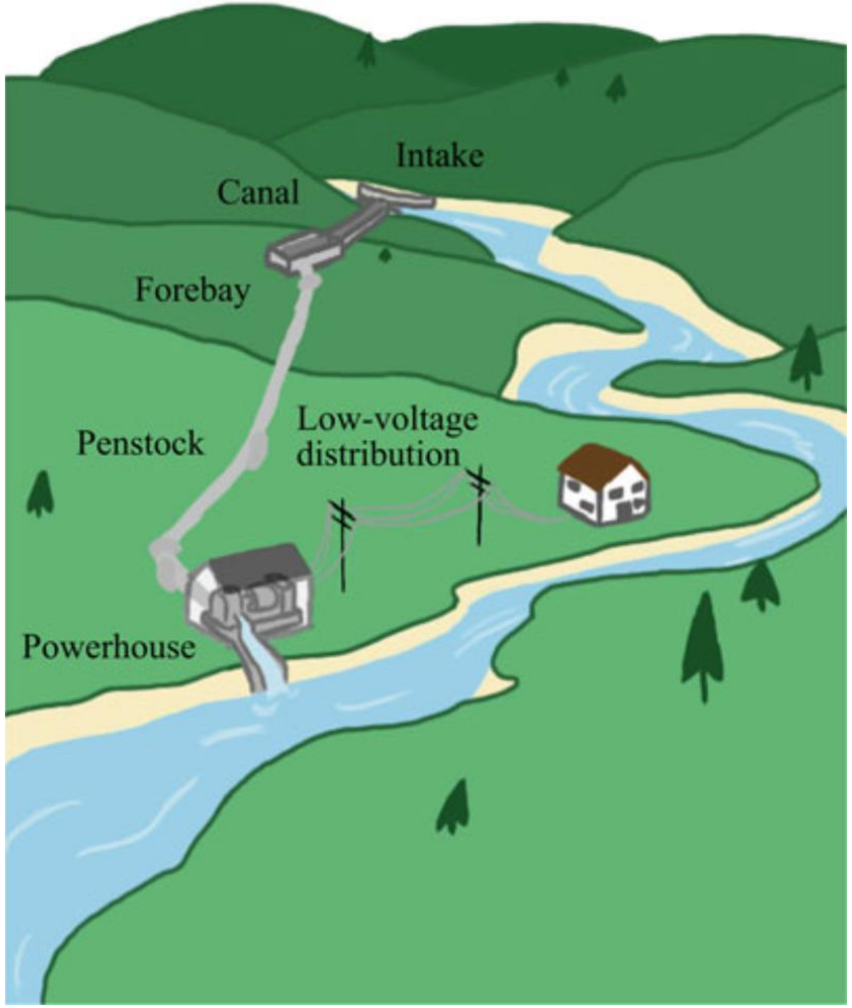
Learning Outcomes

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

- ✓understand the principles of micro hydro power generation
- ✓be able to characterize a hydro resource
- ✓describe the importance of turbine selection and matching to the hydro resource

Micro Hydro Power (MHP)

- Turbines convert energy in water into mechanical energy to power a turbine
- Mature technology
- Requires suitable water resource and terrain
- 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
  - Velocity
  - Elevation (above reference plane)
  - Pressure
- Energy from pressure and velocity usually 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, 9.81 m/s^2
z: elevation, m
P_{wa}: pressure, Pa
K: constant, J/m^3

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?

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

Total Head

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

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

$$\underbrace{\frac{1}{2g}v_{\mathrm{wa}}^{2}}_{\text{Velocity head}}+\underbrace{z}_{\text{Elevation head}}+\underbrace{\frac{p_{\mathrm{wa}}}{\rho_{\mathrm{wa}}g}}_{\text{Pressure head}}=H_{\mathrm{t}}$$

- H_t: total head, m

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 total energy in a volume of water is related to total head as:

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

- V_{wa}: volume of water (m^3)
- $E_{wa,total}$: total energy in a volume of water (J)

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

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

Recall: PE = 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

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

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

$$H_t = \frac{1}{2 \times 9.81} 1^2 + 38 + \frac{101,325}{1000 \times 9.81} = 0.05 + 38 + 10.33 = 48.38m$$

Example

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.

Also note that most of the total head comes from the elevation head

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

$$H_t = \frac{1}{2 \times 9.81}1^2 + 38 + \frac{101,325}{1000 \times 9.81} = 0.05 + 38 + 10.33 = 48.38m$$

Exercise

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

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

Effective Head

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

Effective Head < Total Head

Effective head and Total head

- Difference between total head and effective head are 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 hydroturbine (and reducing its potential energy)

$$\mathbf{H} = \mathbf{z} - \mathbf{H}_{\mathrm{f}} = \mathbf{z}\,\eta_{\mathrm{convey}}$$

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

Hydro Resource

- Useable energy in a volume of water

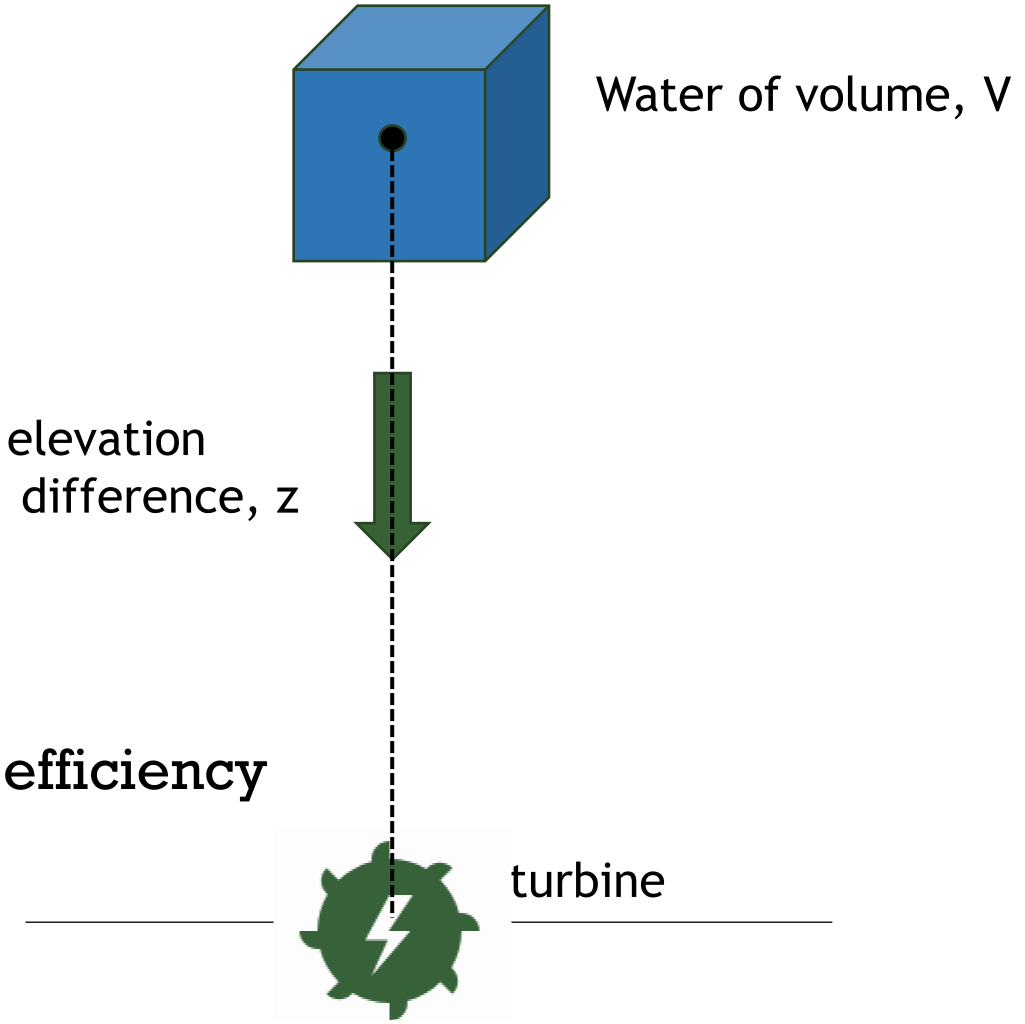
$$E_{wa} = g \times H \times m_{wa} = g \times H \times \rho_{wa} \times V$$

- 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

$$H = z \times \text{conveyance system efficiency}$$



Exercise

The water resource for MHP scheme has an effective head of 38 m. The flow rate is 0.005 m^3/s (5 liters per second). Compute power available to the input of the turbine.

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

$$P_{wa} = 1000 \times 9.8 \times 38 \times 0.005 = 1862W$$

Power Extraction

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

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

  - $P_{d,turbine}$: 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 MHP scheme is at an elevation of 38 m. The flow rate is 0.005 m^3/s (5 liters per second). The conveyance system efficiency is 90% and the turbine efficiency is 85%. Compute the power extracted by the turbine.

Note: in this problem, we are given the elevation, not the effective head.

Exercise

- The water resource for MHP scheme is at an elevation of 38 m. The flow rate is 0.005 m^3/s (5 liters per second). The conveyance system efficiency is 90% and the turbine efficiency is 85%. Compute the power extracted by the turbine.

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

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

$$P_{wa} = 1000 \times 9.8 \times 34.2 \times 0.005 = 1677.5\text{W}$$

$$P_{d,turbine} = \eta_{turbine} P_{wa} = 0.85 \times 1677.5 = 1425.9\text{W}$$

Water Intake

Only a portion of the stream is diverted for MHP use

(courtesy Joe Butchers)

(courtesy Joe Butchers)

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Intake

Removeable boards to clear silt/debris

Water passes through grate into penstock (not visible)

Penstock

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

(courtesy Joe Butchers)

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Turbine Types

Pelton

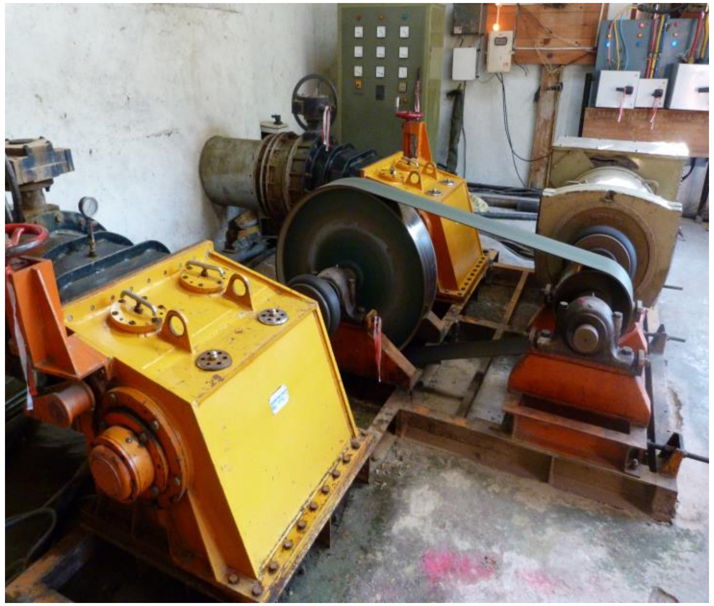
Francis

Crossflow

Turgo

Turbine coupled to generator

(courtesy Joe Butchers)



(courtesy Joe Butchers)

Turbine Selection

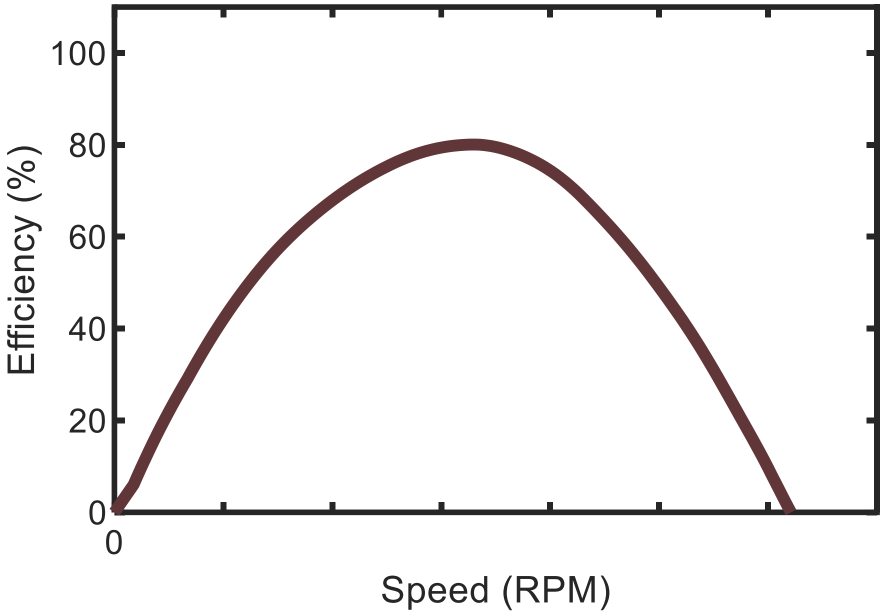
- Several types of hydro turbines
- Most water resources for MHP are high head or medium head

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

Turbine Selection

- Select turbine that will operate most efficiently given the power and rotational speed requirements, and the water resource speed and head
  - Turbine Application Chart
  - Calculate using “specific speed”

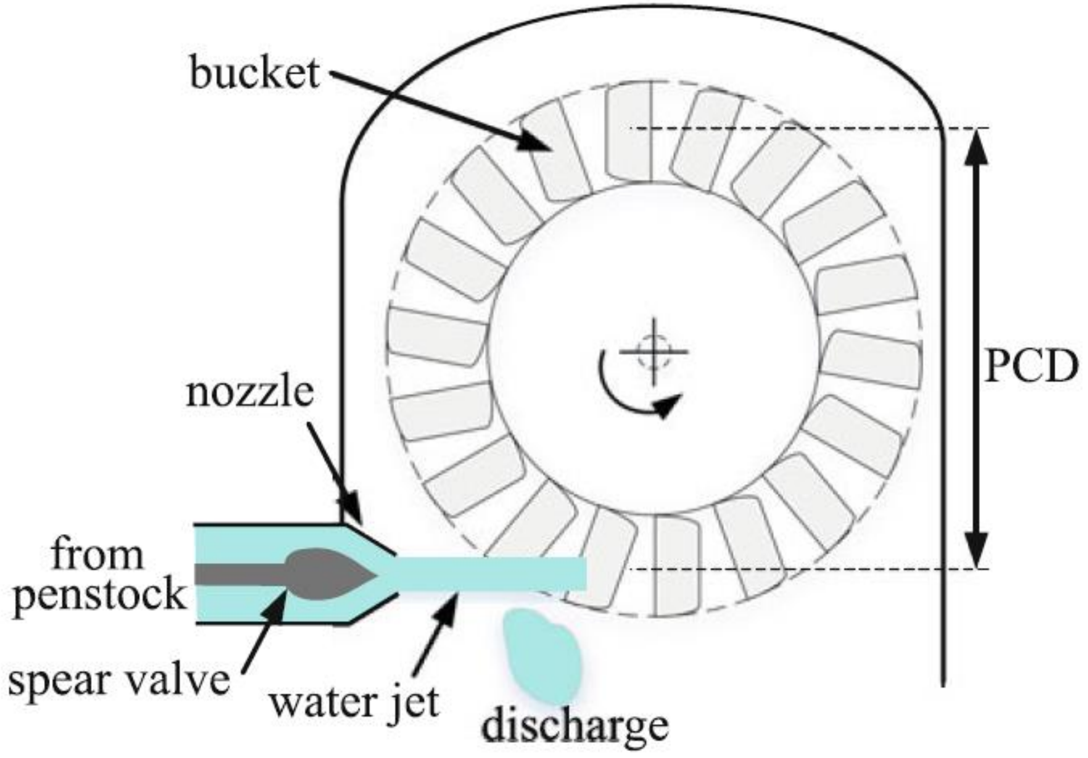
Illustrative efficiency curve for Pelton Turbine



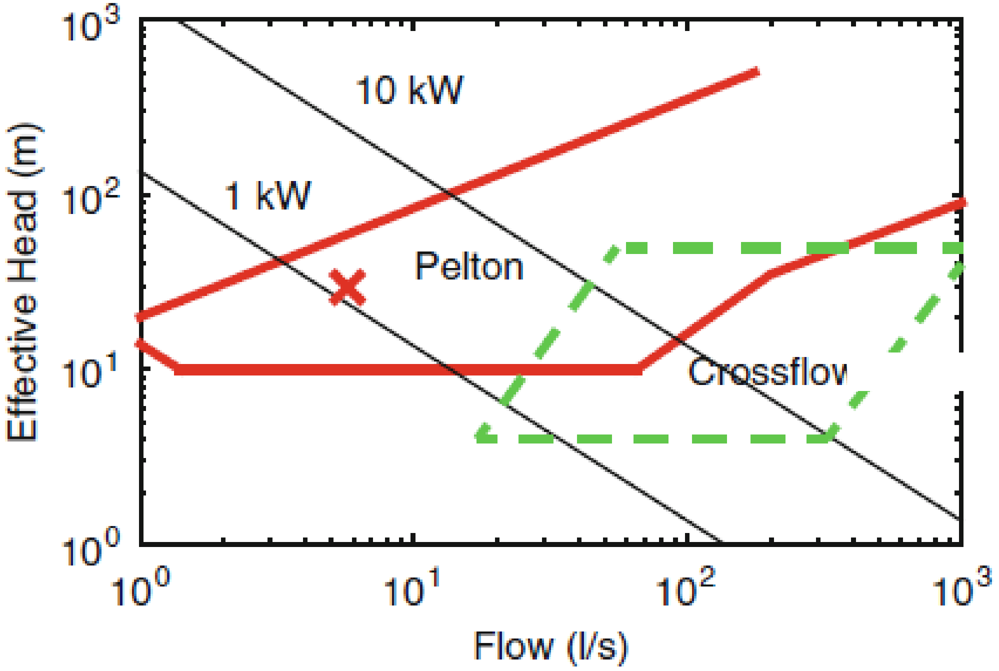
Speed Matters

- 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

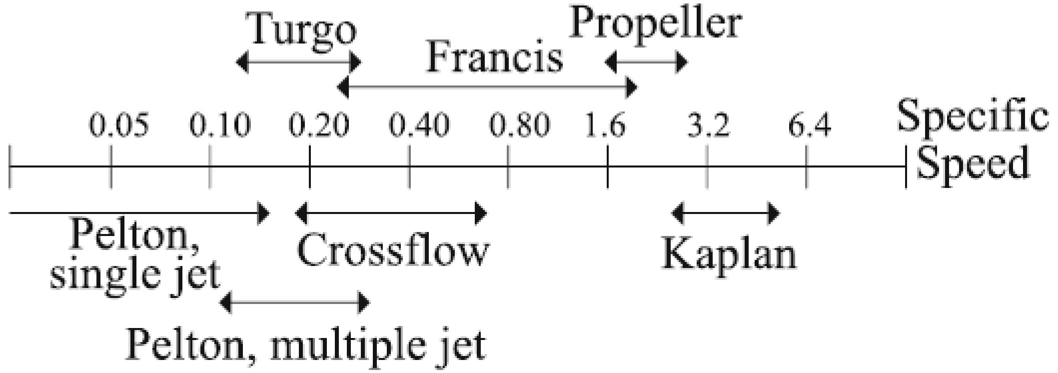


Turbine Application Chart



Specific Speed (Dimensionless)

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

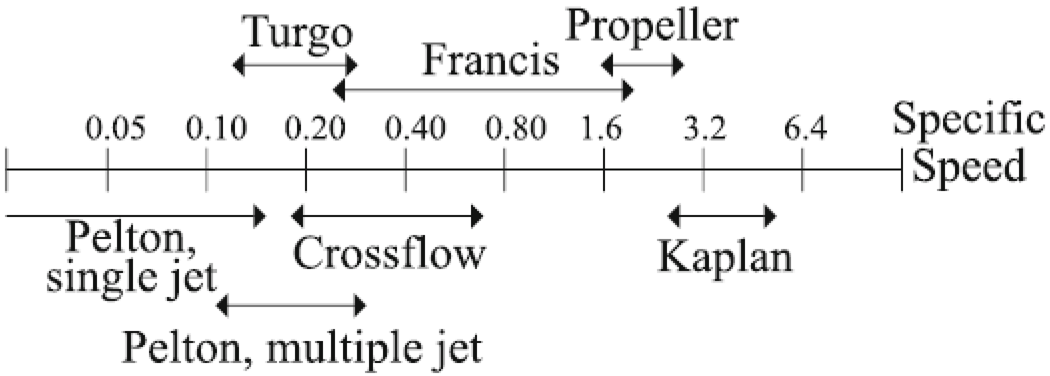


ω_m: rotational speed of turbine, rad/s
g: gravitational constant, m/s^2
H: effective head, m
Q: water flow rate, m^3/s

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

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

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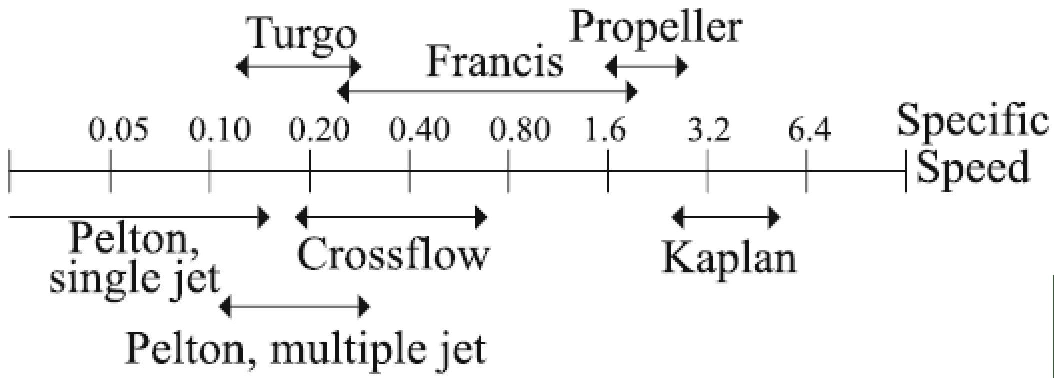
$$S = \frac{\omega_m \sqrt{P_{\text{d,turbine}} / \rho_{\text{wa}}}}{(gH)^{5/4}} = \frac{\frac{2\pi}{60} \times 1500\sqrt{1250/1000}}{(9.81 \times 30)^{5/4}} = 0.144$$



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

Exercise

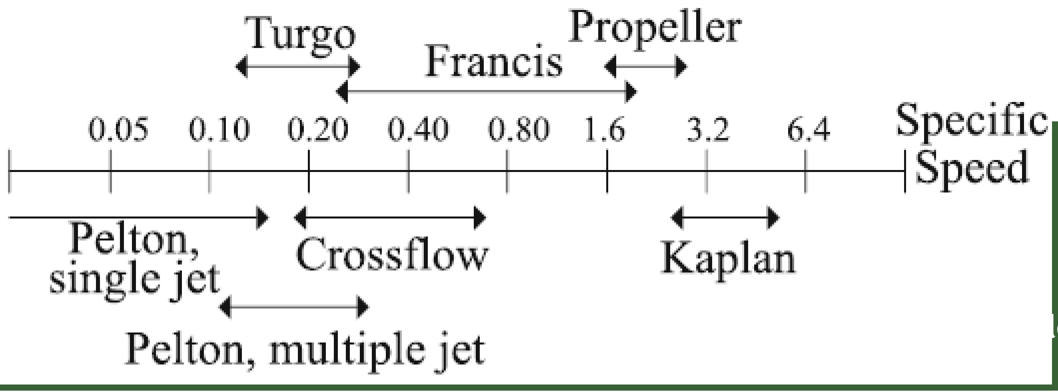
- Compute the dimensionless specific speed for a water resource with an effective head of 10m. Assume the turbine will rotate 1500 RPM with a developed mechanical power of 1.25 kW. What turbine(s) would be suitable for this application?

Exercise

- Compute the dimensionless specific speed for a water resource with an effective head of 10m. 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?

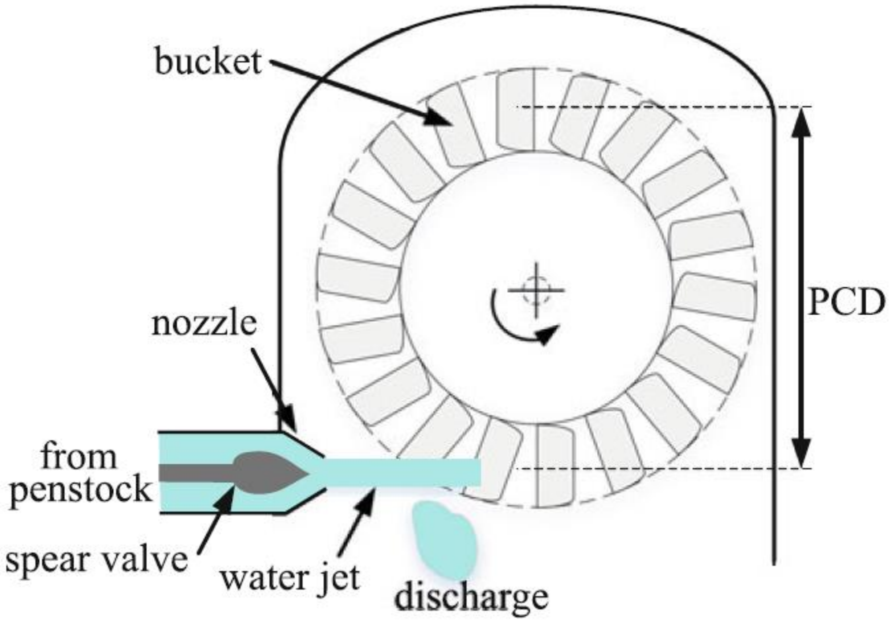
$$S = \frac{\omega_m \sqrt{P_{d,\text{turbine}} / \rho_{wa}}}{(gH)^{5/4}} = \frac{\frac{2\pi}{60} \times 1500\sqrt{1250/1000}}{(9.81\times 10)^{5/4}} = 0.568$$

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



Turbine Design

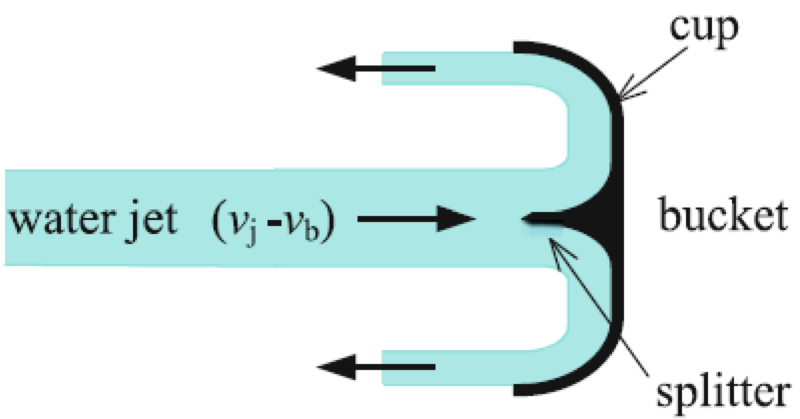
- We will consider the design of a single-nozzle pelton turbine to see how the characteristics of the hydro resource interplay with our design decisions



PCD: Pitch Circle Diameter

Pelton Turbines

- The 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?



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

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

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

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

The 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

- The maximum power developed by the turbine is then

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

- 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 keep the turbine operating an optimal speed, if we increase the water jet velocity we must also increase the bucket speed

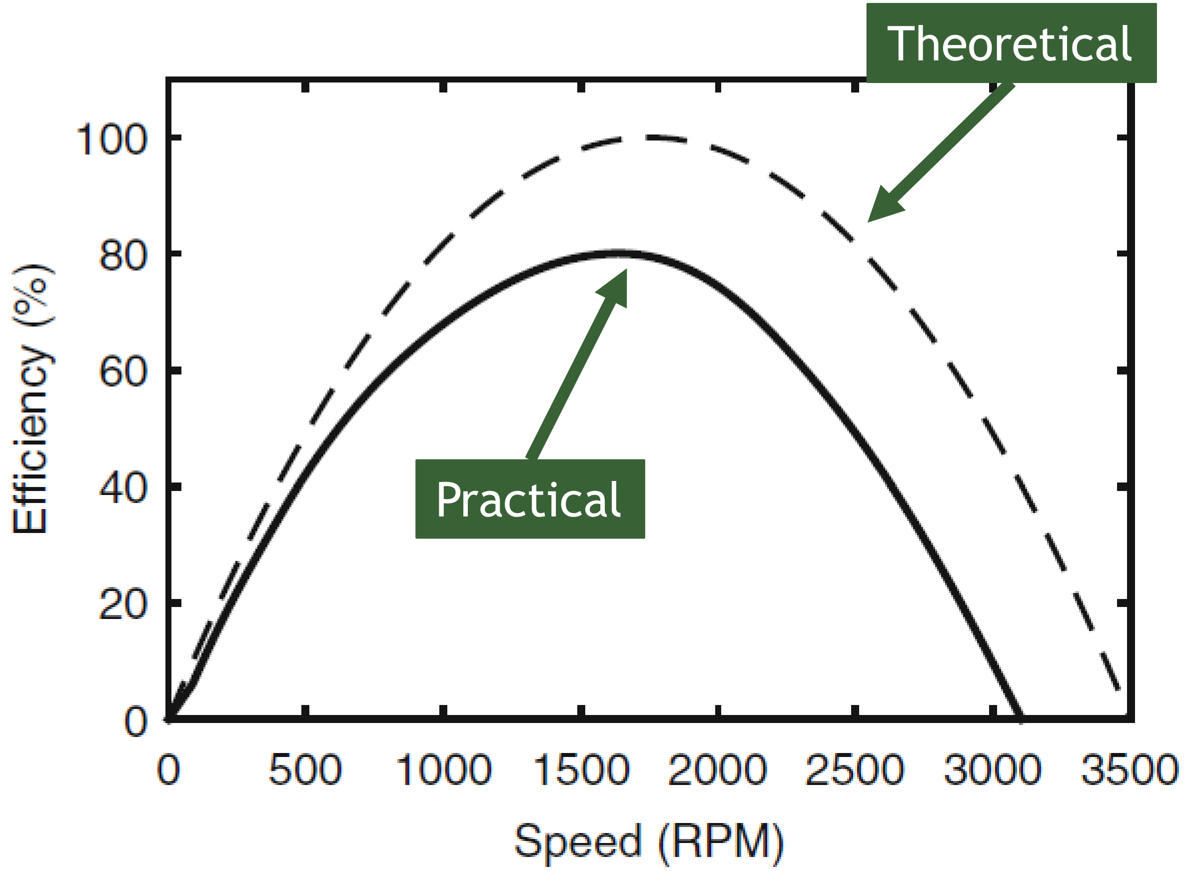
$$P^{*}_{\mathrm{d,turbine}} = \frac{1}{2}\rho_{\mathrm{wa}} Q v_{\mathrm{j}}^{2}$$

Pelton Turbine Efficiency

- The efficiency is expressed as

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

- Theoretical efficiency is 100%,
- Actual efficiency is ~50-85%, with maximum efficiency closer t oy = 0.46



Pelton Turbine Design

- We know we should design our turbine so that the turbine rotates at 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

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

We see the jet velocity depends on the effective head of the resource

Speed Equation

- Rotational speed of the turbine is:

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

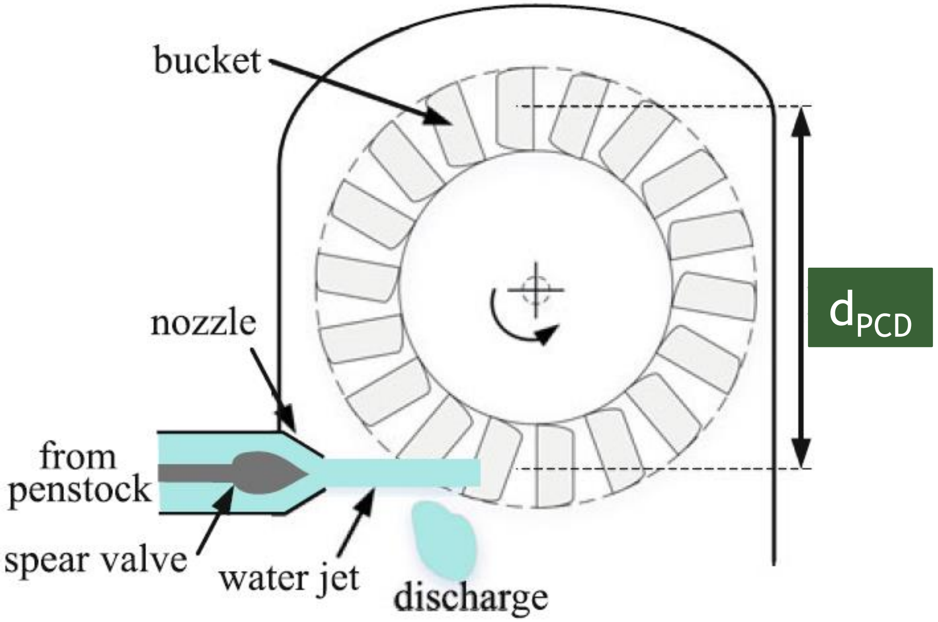
tangential velocity = radius x angular velocity

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

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

This is the "speed equation"

N_m: speed, in RPM



Speed Equation

- We can re-write the speed equation in terms of the effective head of the water resource as:

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

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

- We now have an 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

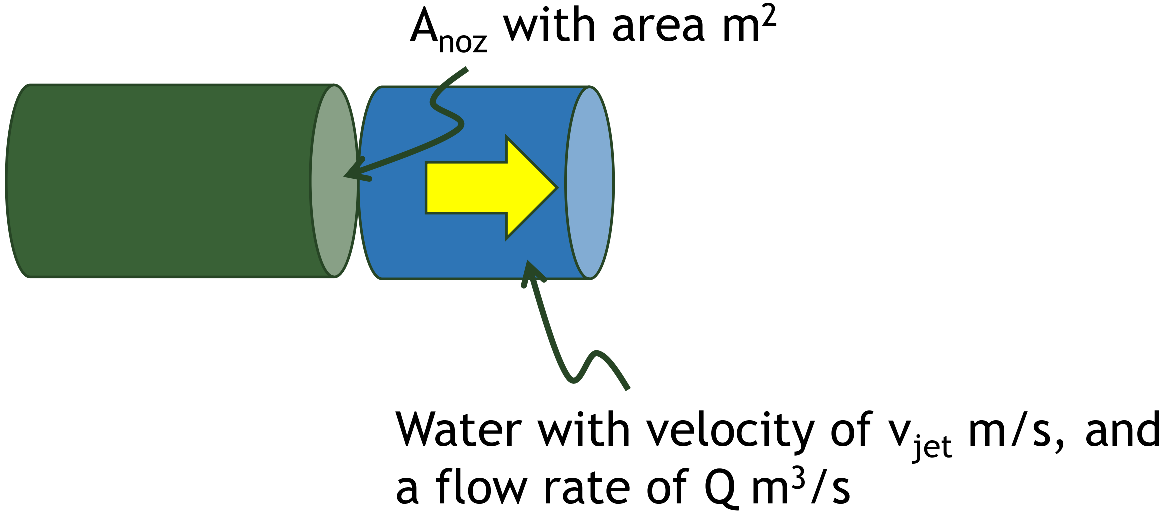
$$d_{\text{PCD}} \geq \frac{d_{\text{jet}}}{0.11}$$

- 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:

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



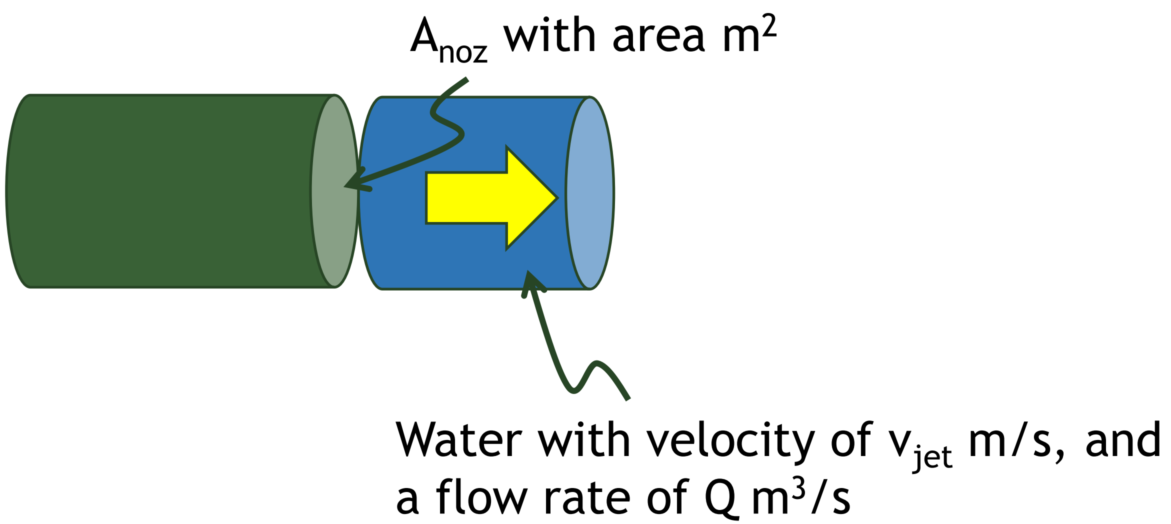
Nozzle Diameter

- 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 every thing remains the same):
  - Increase
  - Decrease
  - The diameter is not affected by flow rate

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

Exercise

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

Exercise

- If the head of the system is increased, but the flow rate remains the same, the diameter of the jet must
  - Increase
  - Decrease
  - The diameter of the jet is not affected by the head

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

Example

- Assume a Pelton turbine is directly coupled to a four-pole synchronous generator. The generator is to produce 50Hz 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.

Example

- 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

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

$$Q = \frac{P_{wa}}{\rho_{wa} \times g \times H} = \frac{11{,}111}{1000 \times 9.81 \times 70} = 0.0162 \text{ m}^3/\text{s}$$

Example

- Now determine the PCD from

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

This is a four pole machine designed to output 50Hz, so the speed is 3000/2 = 1500 RPM

$$d_{\mathrm{PCD}} = \frac{y \times \sqrt{2gH} \times 60}{\pi N_{\mathrm{m}}} = \frac{0.5 \times \sqrt{2 \times 9.81 \times 70} \times 60}{\pi \times 1500} = 0.2359 \text{ m} \approx 9.25 \text{ inches}$$

Example

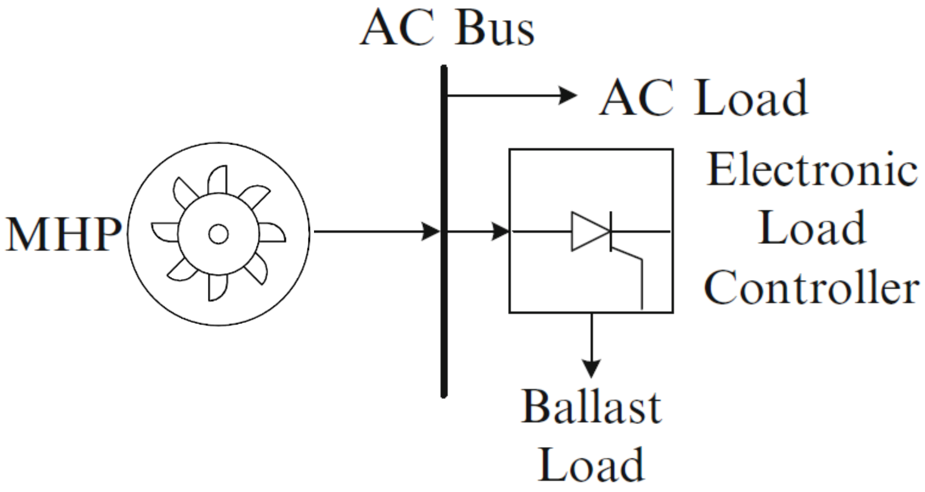
- Finally, determine the diameter of the jet

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

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

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)



Micro Hydro Power

- Relatively inexpensive
- Simple to operate
- No fuel costs
- Long operational life
- Consistent power production---no need for batteries
- Renewable resource
- No emissions
- Mature technology

- Adequate water resource not widely available
- High up-front costs
- Water resource characteristics (flow rate, head, and effects of seasonality) must be assessed
- Must be custom-designed
- Commercially-available turbines might not match the site characteristics
- Many stakeholders affected—permits and permissions might be required

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