ME-251: Thermodynamics and energetics I
Open Systems II

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Photo Credit: Trougnouf

ETA-Lab
Energy Transport Advances

Last Time

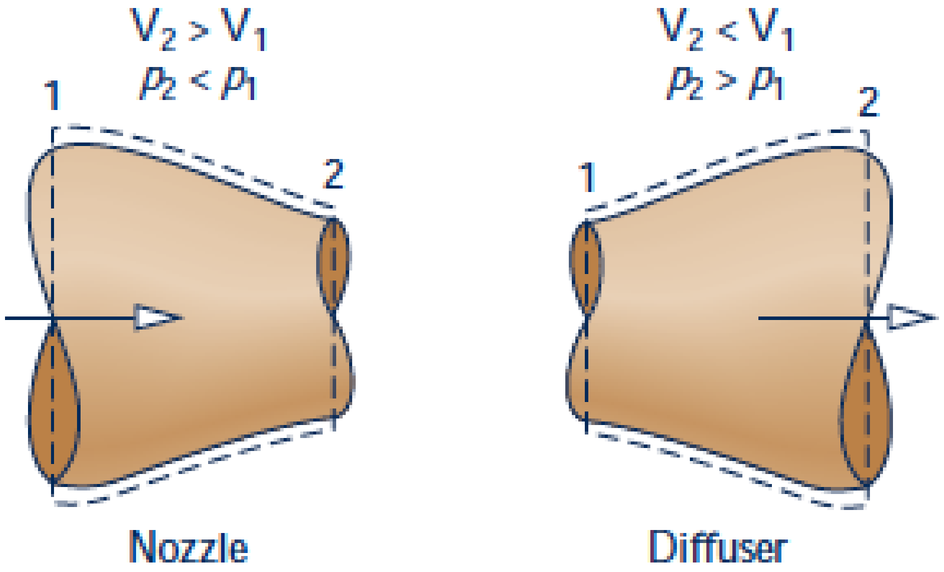
- Energy and mass balance of open systems

ILOs Today

- Model real-world open-system examples (steady-state analysis)
  - Nozzles and diffusers
  - Turbines
  - Compressors and pumps
  - Heat exchangers
  - Throttling devices

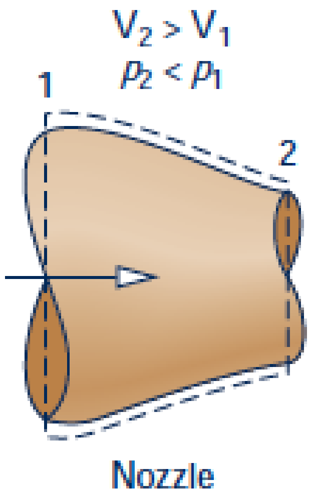
- Reading: 4.6-4.11

Nozzles and Diffusers

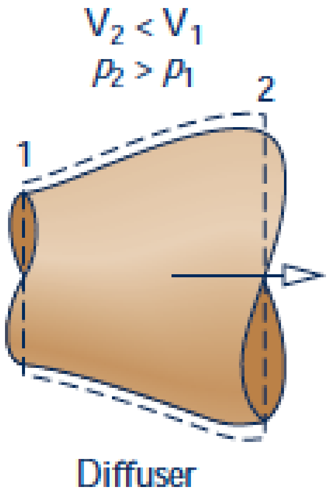


- A **nozzle** is a flow passage of varying cross-sectional area in which the velocity of a gas or liquid increases in the direction of flow.
- In a **diffuser**, the gas or liquid decelerates in the direction of flow.

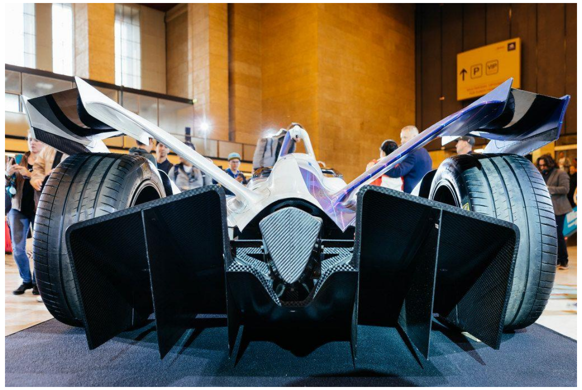
Nozzles and Diffusers



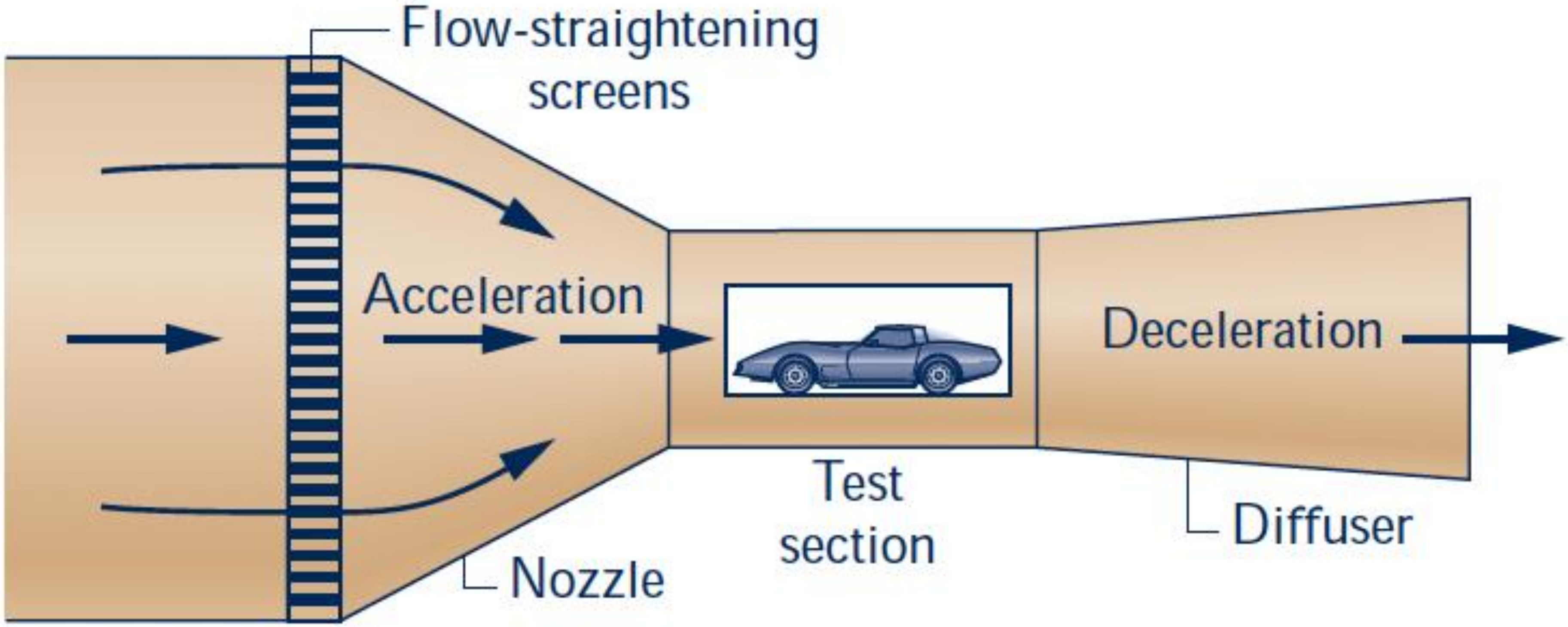
Garden hose nozzle



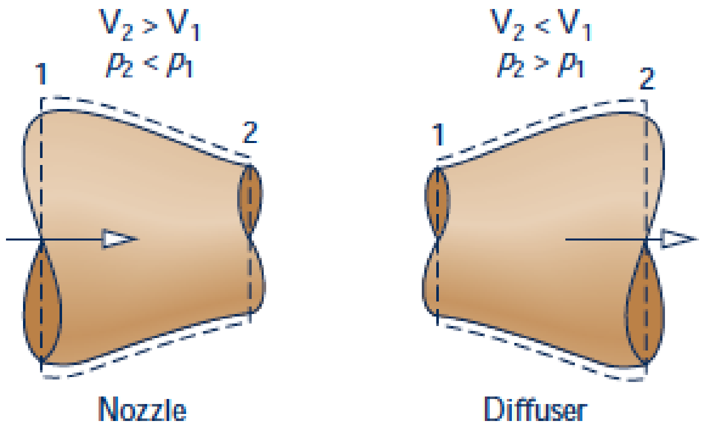
Race car diffuser



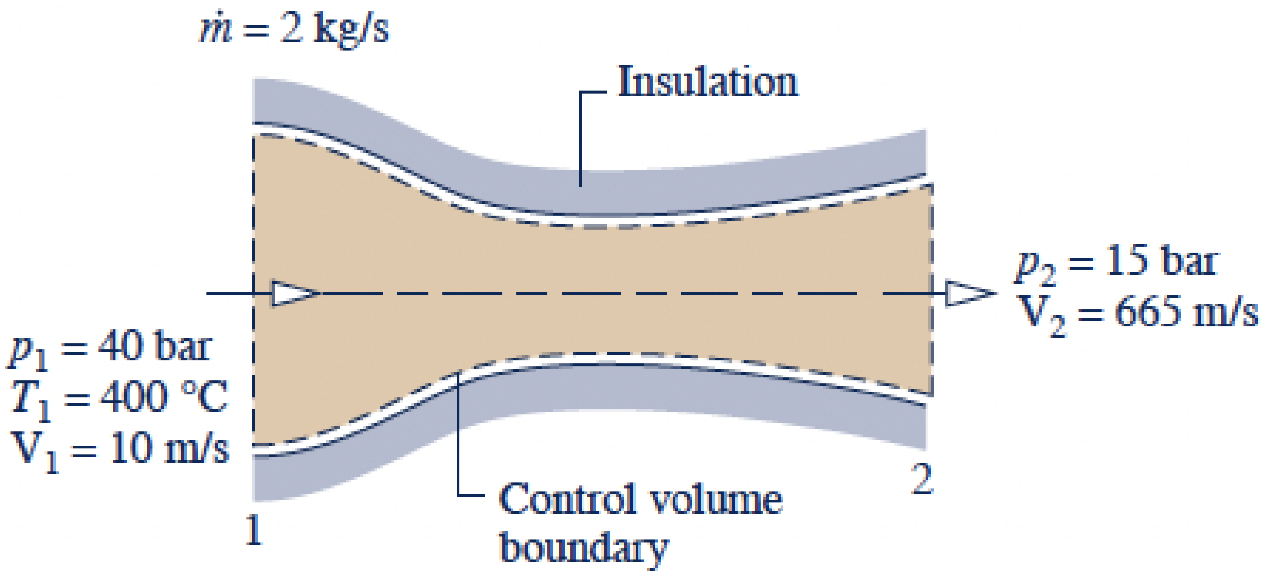
Wind Tunnel


Flow-straightening
screens
Acceleration
Test
section
Deceleration
Nozzle
Diffuser

Modeling Nozzles and Diffusers



Example: Steam Nozzle



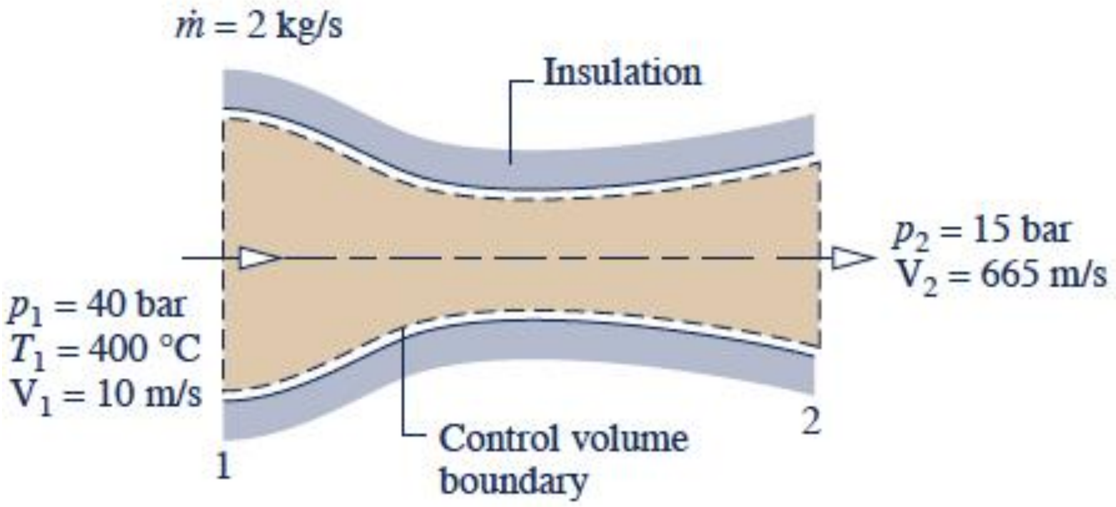
Steam enters a converging-diverging nozzle reaching a steady state

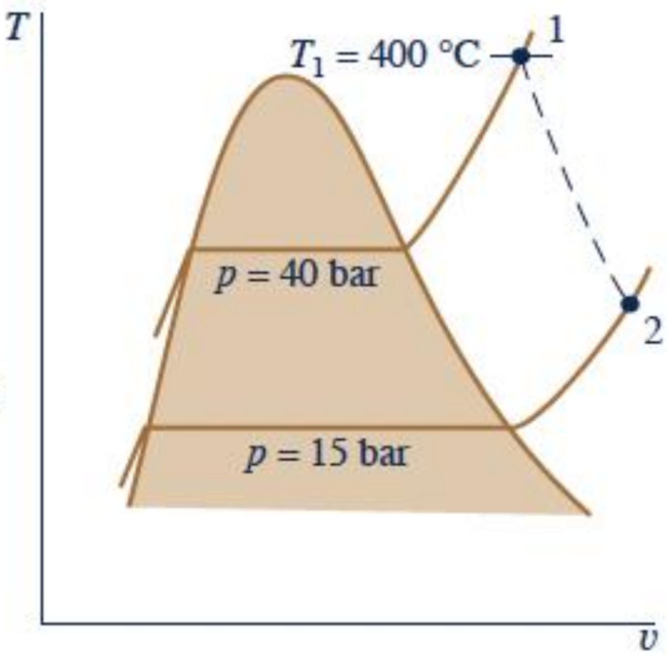
Heat transfer is negligible with the surrounding

Potential energy change can be neglected

Determine the exit area

Example: Steam Nozzle





$$\dot{Q}_{cv} - \dot{W}_{cv} + \dot{m}\left(h_1 + \frac{\vec{V}_1^2}{2} + gz_1\right) - \dot{m}\left(h_2 + \frac{\vec{V}_2^2}{2} + gz_2\right) = 0$$

Relation to Bernoulli's Principle

Common form of Bernoulli's principle $$\frac{\vec{V}^2}{2} + gz + pv = \text{const}$$

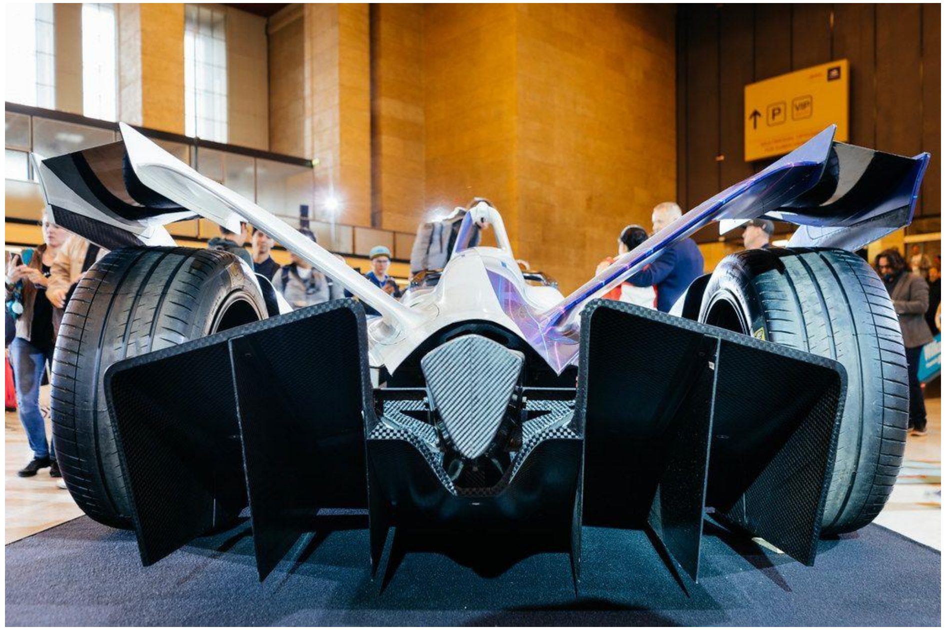
Ignoring potential energy change $$\frac{\vec{V}^2}{2} + pv = \text{const}$$

Nozzle/diffuser ignoring heat transfer $$h_1 + \frac{\vec{V}_1^2}{2} + gz_1 = h_2 + \frac{\vec{V}_2^2}{2} + gz_2$$

Relation to Bernoulli's Principle

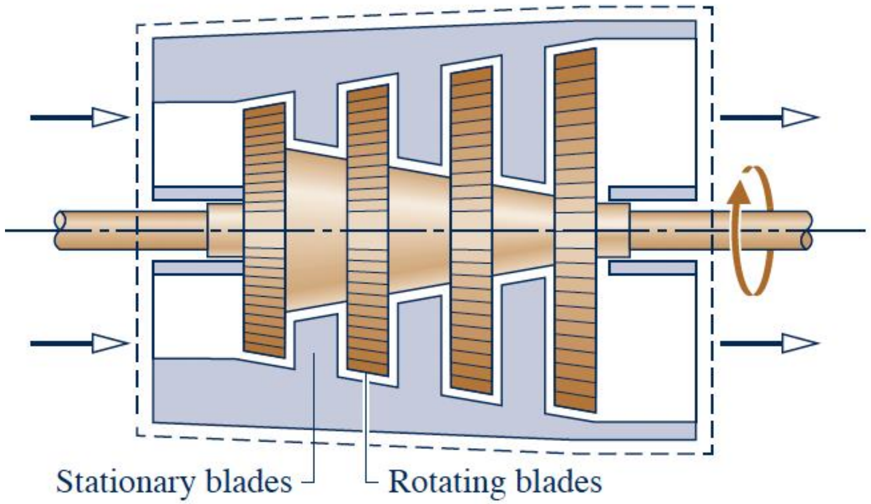
$$h_1 + \frac{\vec{V}_1^2}{2} + gz_1 = h_2 + \frac{\vec{V}_2^2}{2} + gz_2$$

Race Car Diffuser

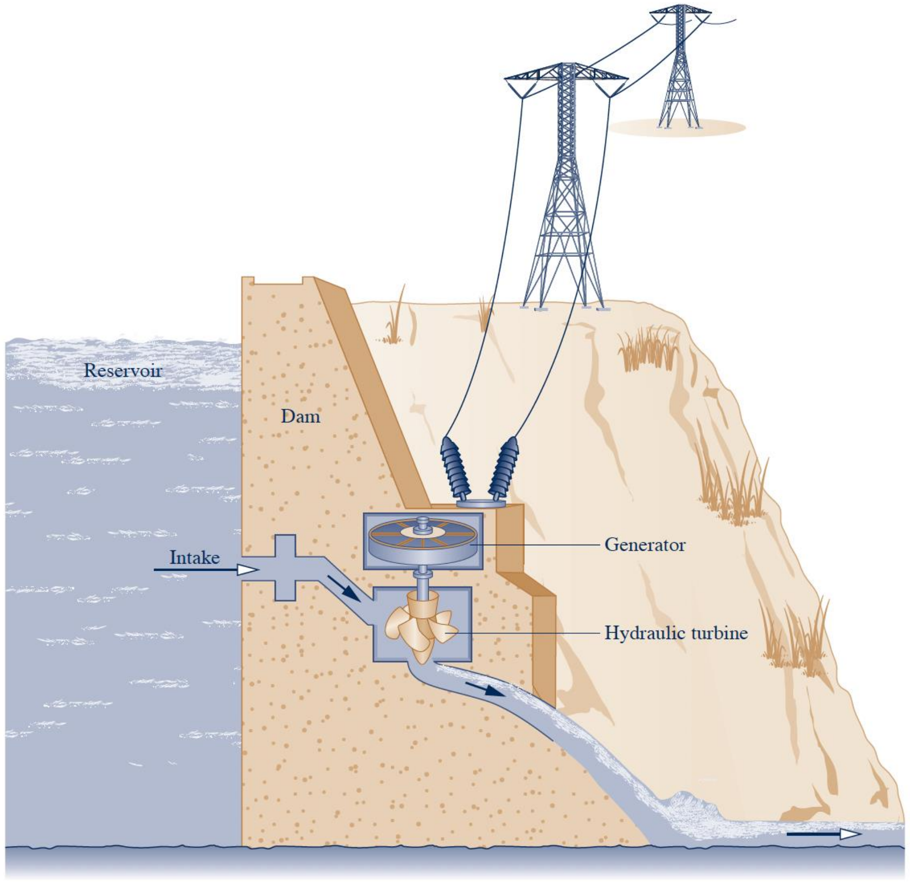


Turbine

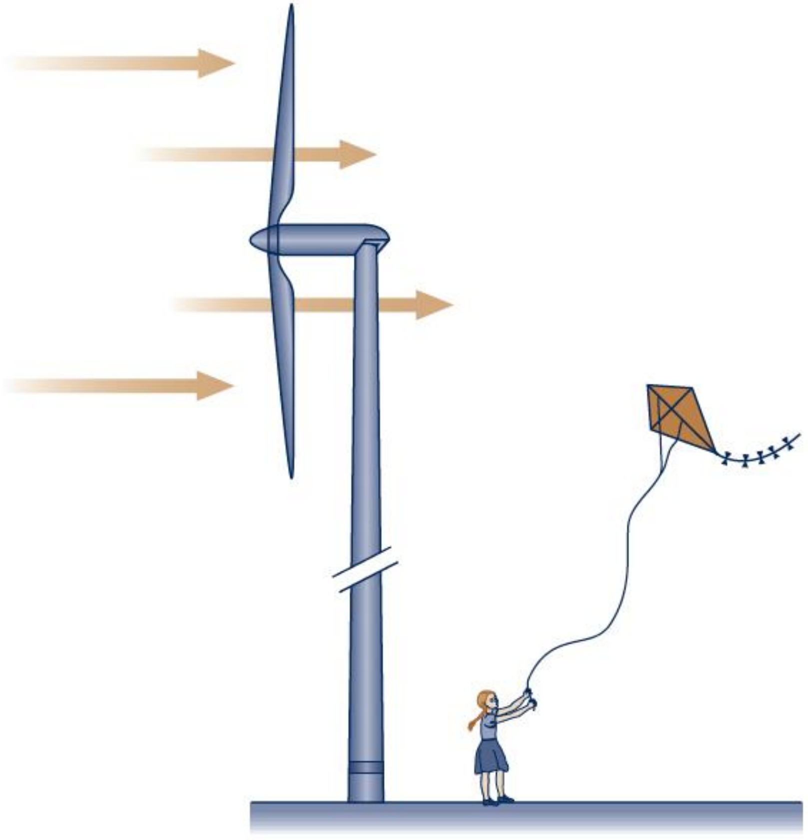
- A **turbine** is a device in which power is developed as a result of a gas or liquid passing through a set of blades attached to a shaft free to rotate



Turbine

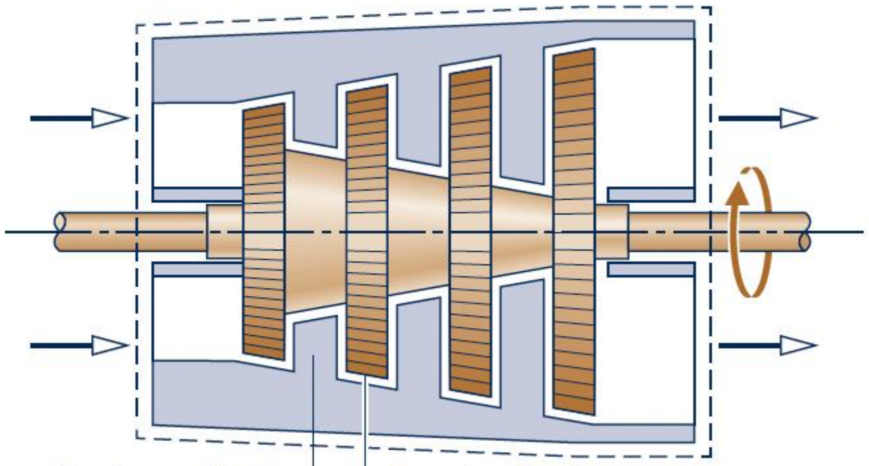


Hydraulic turbine



Wind turbine

Modeling Steam and Gas Turbine

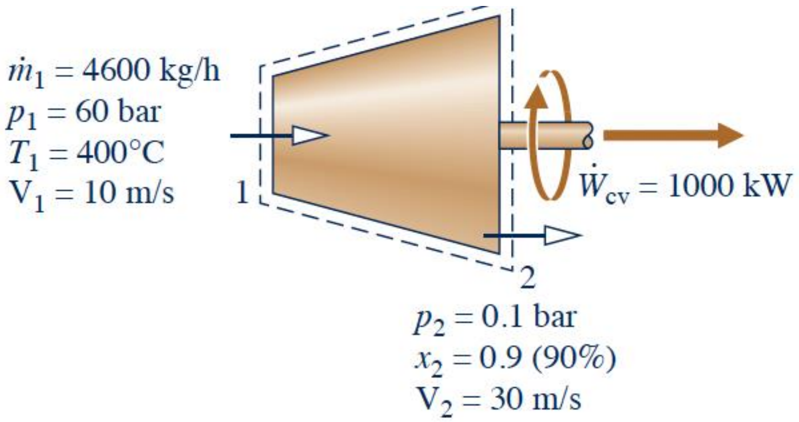


$$\dot{Q}_{cv} - \dot{W}_{cv} + \dot{m}\left(h_1 - h_2 + \frac{V_1^2 - V_2^2}{2} + g(z_1 - z_2)\right) = 0$$

One inlet and one exit

$$\dot{m}_i = \dot{m}_e = \dot{m}$$

Moran Example 4.4



A steam turbine at a steady state with known mass flow rate, power output, and states of the steam at the inlet and exit

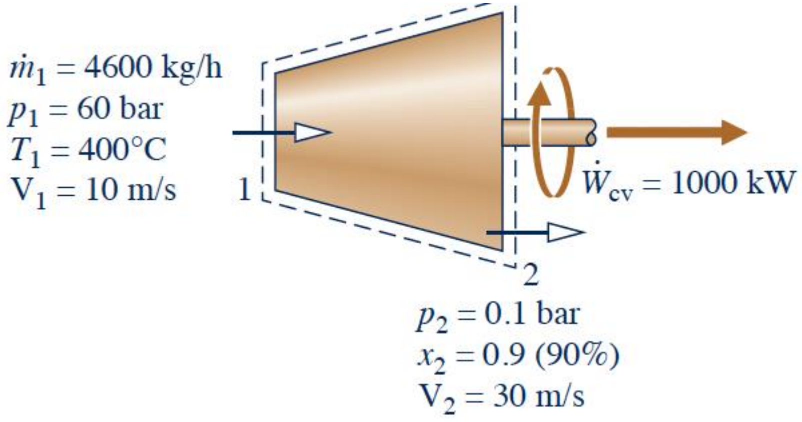
Ignore changes in potential energy

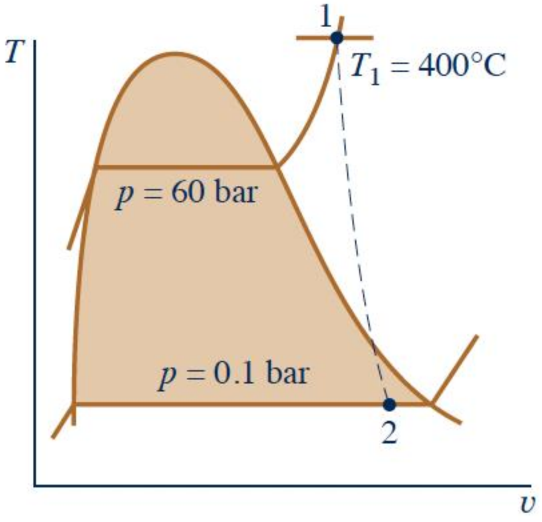
Calculate the rate of heat transfer

Control volume: dashed box

$$\dot{Q}_{cv} - \dot{W}_{cv} + \dot{m}\left(h_1 - h_2 + \frac{V_1^2 - V_2^2}{2} + g(z_1 - z_2)\right) = 0$$

Moran Example 4.4

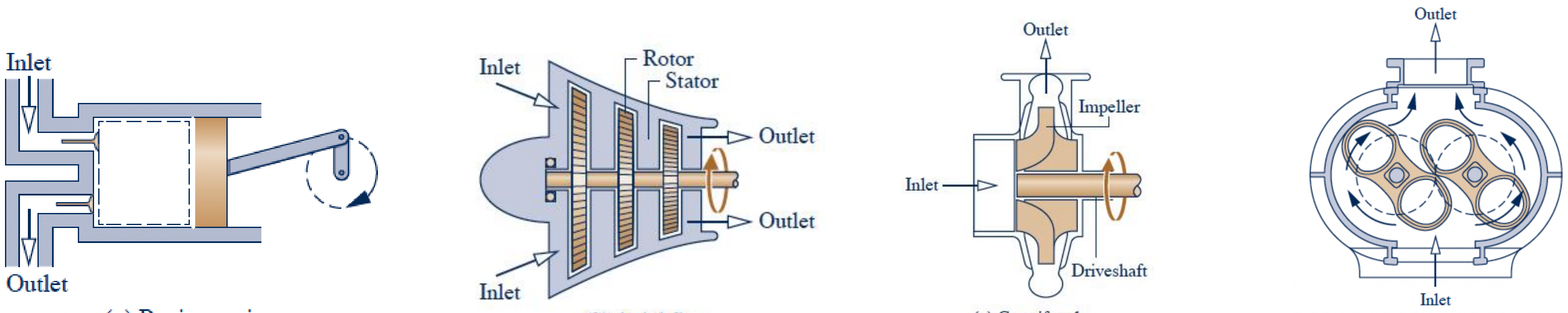




$$\dot{Q}_{cv} - \dot{W}_{cv} + \dot{m}\left(h_1 - h_2 + \frac{V_1^2 - V_2^2}{2}\right) = 0$$

Compressors and Pumps

Compressors and **pumps** are devices in which work is done on the substance flowing through them in order to change the state of the substance, typically **to increase the pressure and/or elevation**.



(*a*) Reciprocating (*b*) Axial flow (*c*) Centrifugal (*d*) Roots type

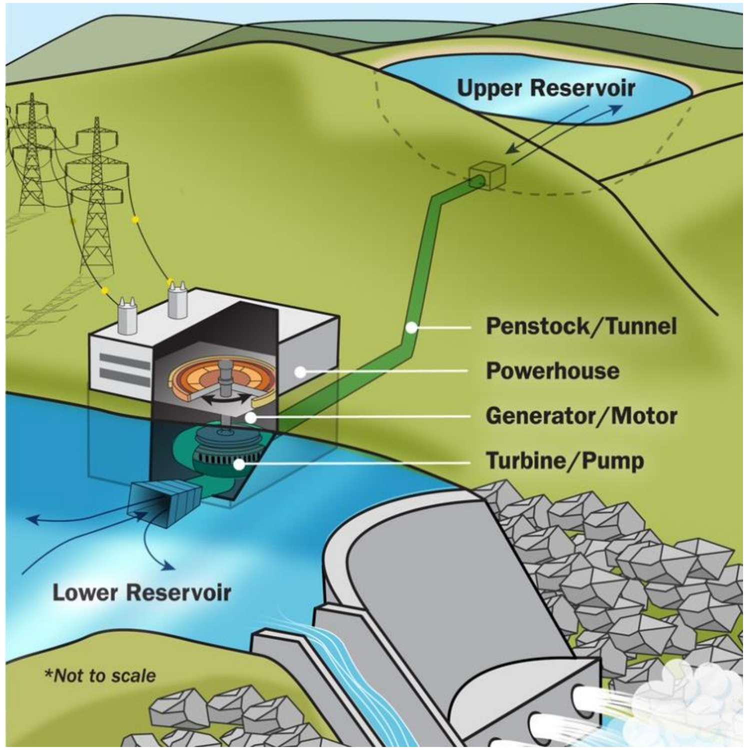
Modeling Compressor and Pump

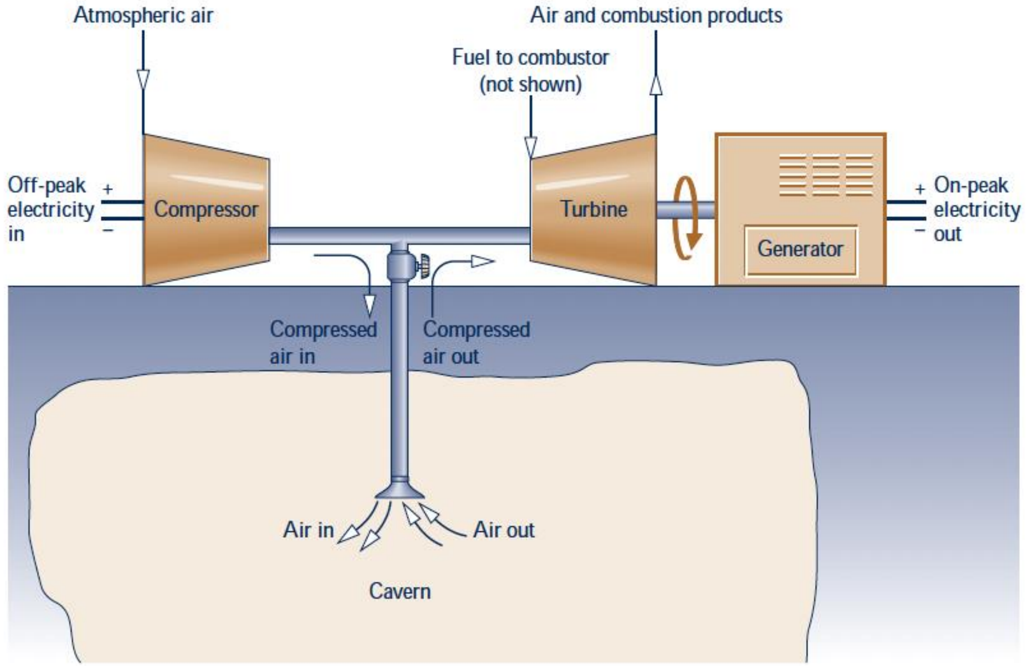
$$\dot{Q}_{cv} - \dot{W}_{cv} + \dot{m}\left(h_1 - h_2 + \frac{V_1^2 - V_2^2}{2} + g(z_1 - z_2)\right) = 0$$

For compressors (gas), the change in kinetic and potential energies are usually negligible compared to the enthalpy change

For pumps (liquid), the change in kinetic and potential energies are often significant

Pumped-Hydro and Compressed-Air Energy Storage

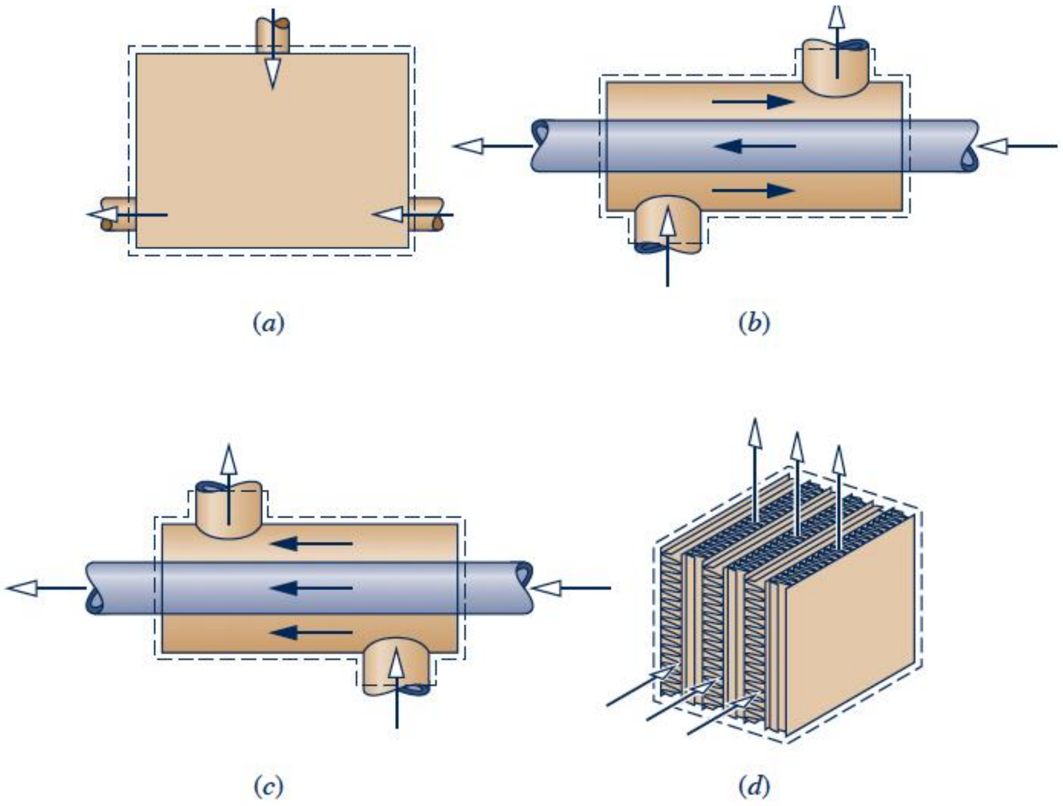




Pump-hydro storage

Compressed-air storage

Heat Exchangers



(a) Direct contact heat exchanger (mixing chamber)

(b) Tube-within-a-tube counterflow heat exchanger

(c) Tube-within-a-tube parallel flow heat exchanger

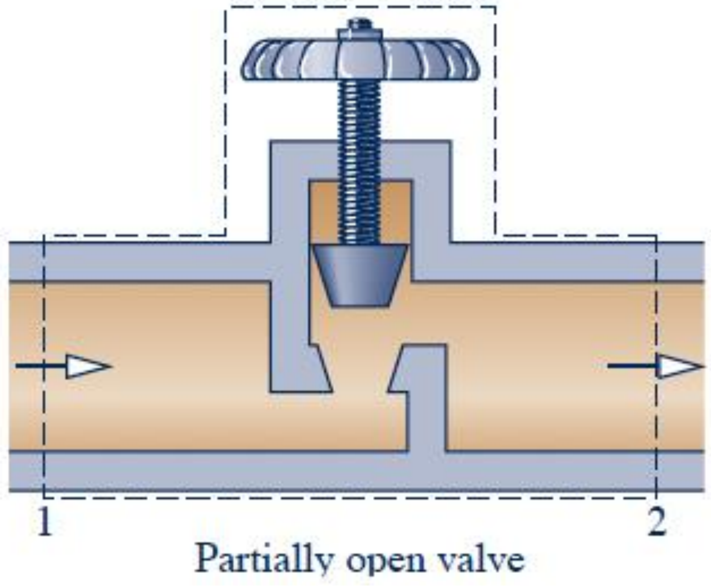
(d) Cross-flow heat exchanger

Modeling Heat Exchangers

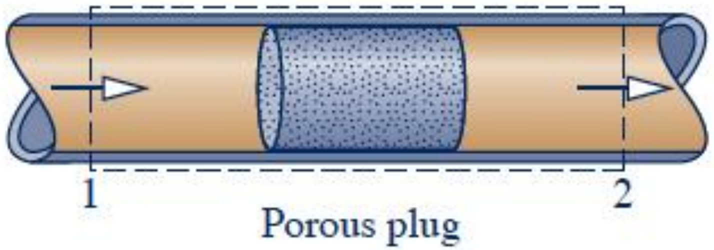
Multi-inlets, multi-exits $\sum_i \dot{m}_i = \sum_o \dot{m}_o$

$$0 = \dot{Q}_{cv} - \dot{W}_{cv} + \sum_i \dot{m}_i \left(h_i + \frac{V_i^2}{2} + g z_i \right) - \sum_e \dot{m}_e \left(h_e + \frac{V_e^2}{2} + g z_e \right)$$

Throttling Devices



Adding a partially opened valve or a porous plug to reduce pressure



One inlet and one exit

$$\dot{m}_i = \dot{m}_e = \dot{m}$$

$$\dot{Q}_{cv} - \dot{W}_{cv} + \dot{m}\left(h_1 - h_2 + \frac{V_1^2 - V_2^2}{2} + g(z_1 - z_2)\right) = 0$$

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