EPFL

ETA-Lab
Energy Transport Advances

ME-251: Thermodynamics and energetics I
Open Systems II

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Photo Credit: Trougnouf

Last Time

- Energy and mass balance of open systems

$$\frac{dm_{cv}}{dt} = \sum_i \dot{m}_i - \sum_o \dot{m}_o$$

$$\frac{dE_{cv}}{dt} = \dot{Q}_{cv} - \dot{W}_{cv} + \sum_i \dot{m}_i \left(h_i + \frac{\vec{V}_i^2}{2} + gz_i \right) - \sum_e \dot{m}_e \left(h_e + \frac{\vec{V}_e^2}{2} + gz_e \right)$$

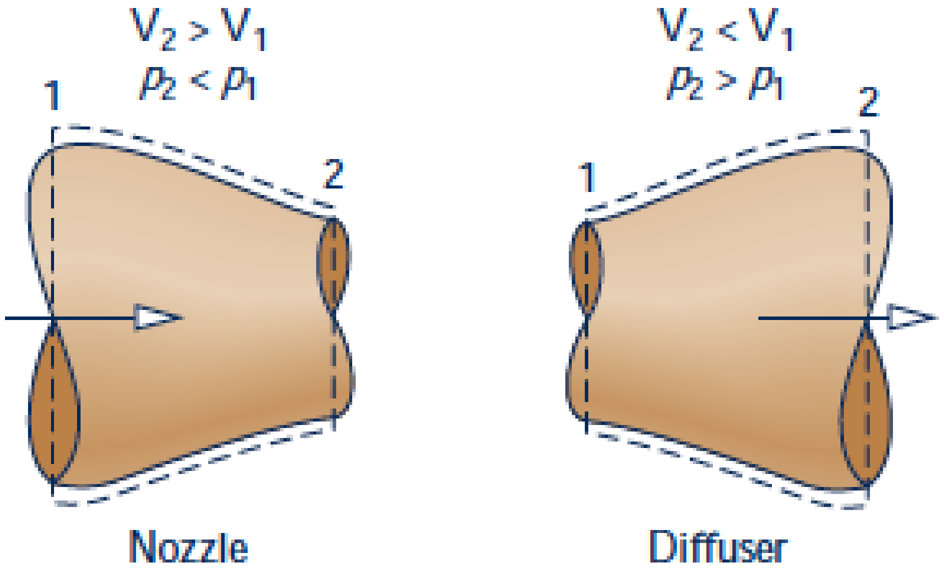
At a steady state $\frac{dm_{cv}}{dt} = 0$ $\frac{dE_{cv}}{dt} = 0$

ILOs Today

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

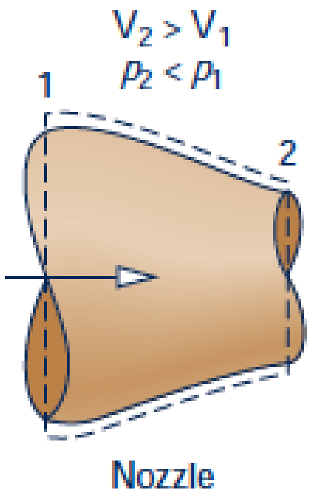
- Reading: 4.6-4.11

Nozzles and Diffusers

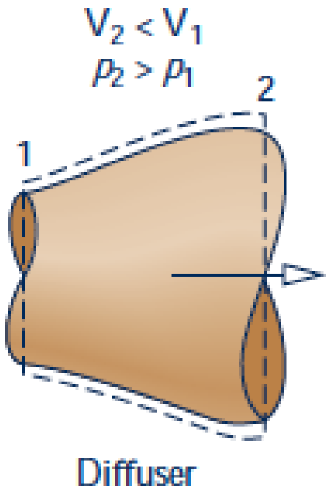


- A **nozzle** is a flow passage of varying cross-sectional area in which the velocity of a gas or liquid increases in the direction of flow.
- In a **diffuser**, the gas or liquid decelerates in the direction of flow.

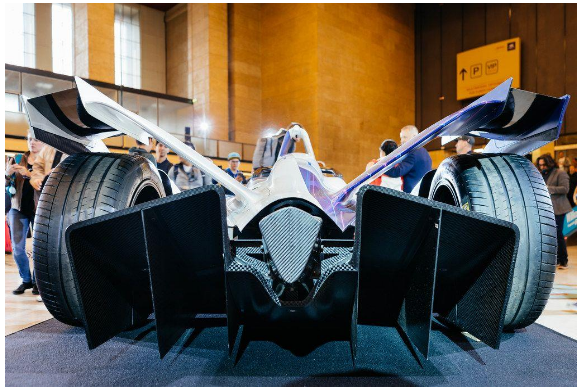
Nozzles and Diffusers



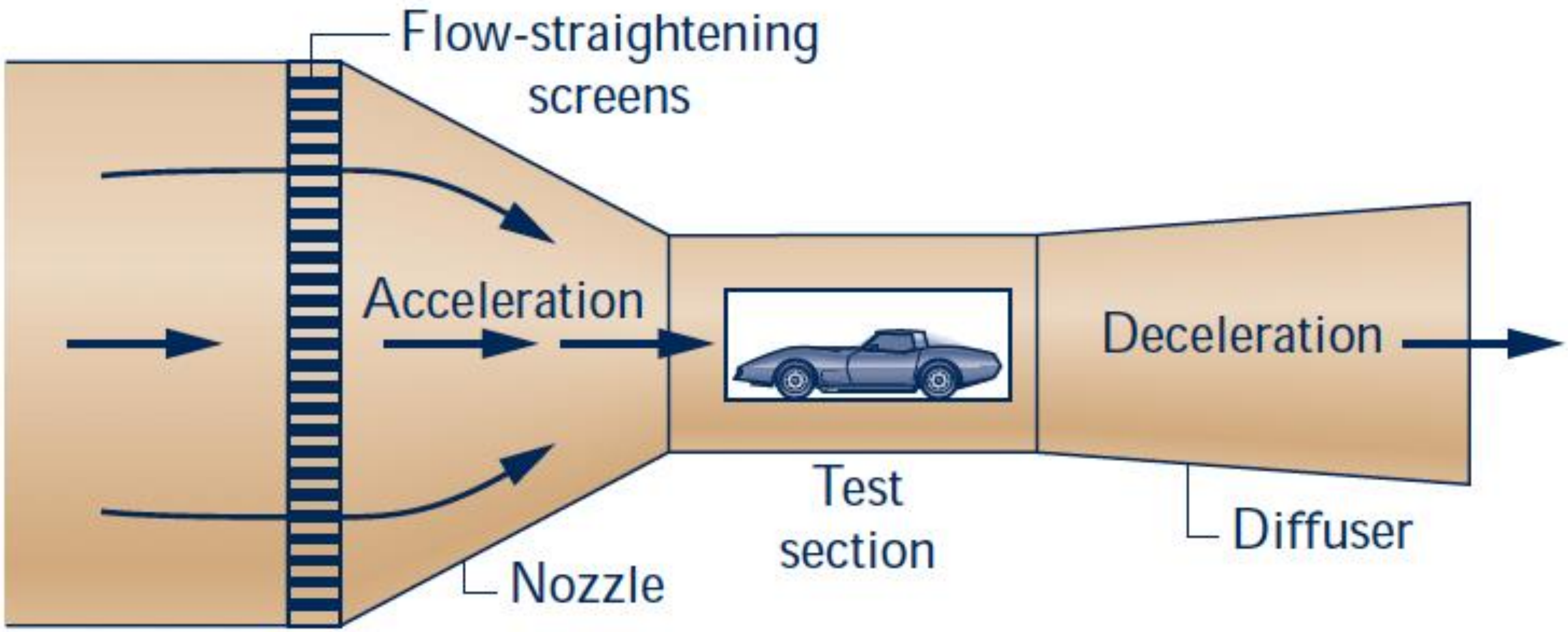
Garden hose nozzle



Race car diffuser

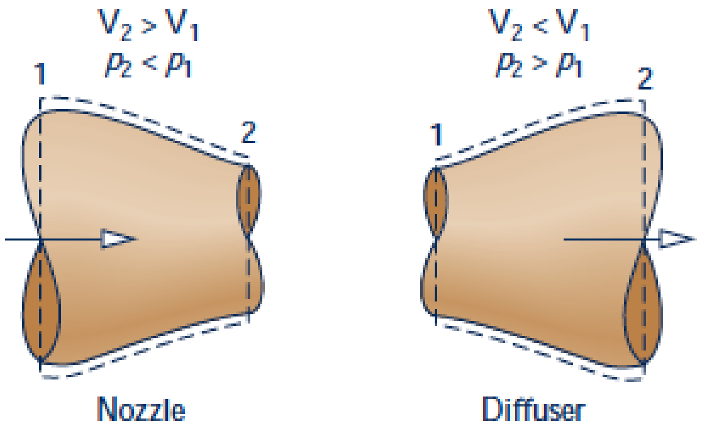


Wind Tunnel


Flow-straightening
screens
Acceleration
Deceleration
Test
section
Nozzle
Diffuser

Modeling Nozzles and Diffusers

Steady state



One inlet and one exit

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

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

There is no work transfer other than flow work, $\dot{W}_{cv} = 0$

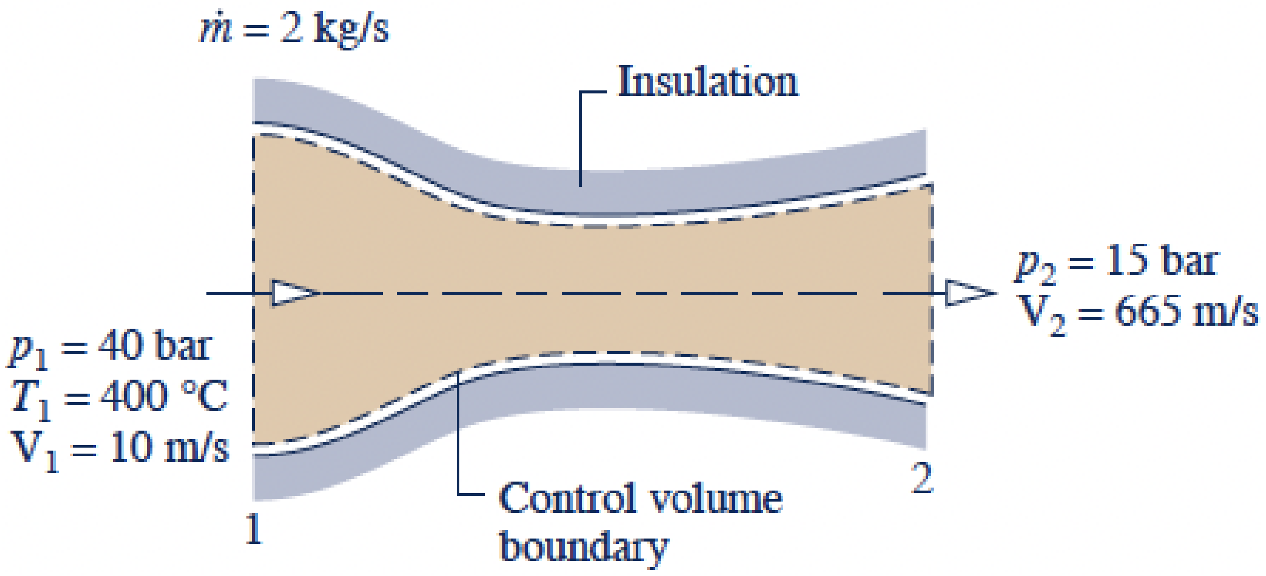
Neglecting heat transfer, $\dot{Q}_{cv} = 0$ (assumption)

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

Further neglecting change in potential energy (assumption)

$$h_1 - h_2 + \frac{\vec{V}_1^2 - \vec{V}_2^2}{2} = 0$$

Example: Steam Nozzle



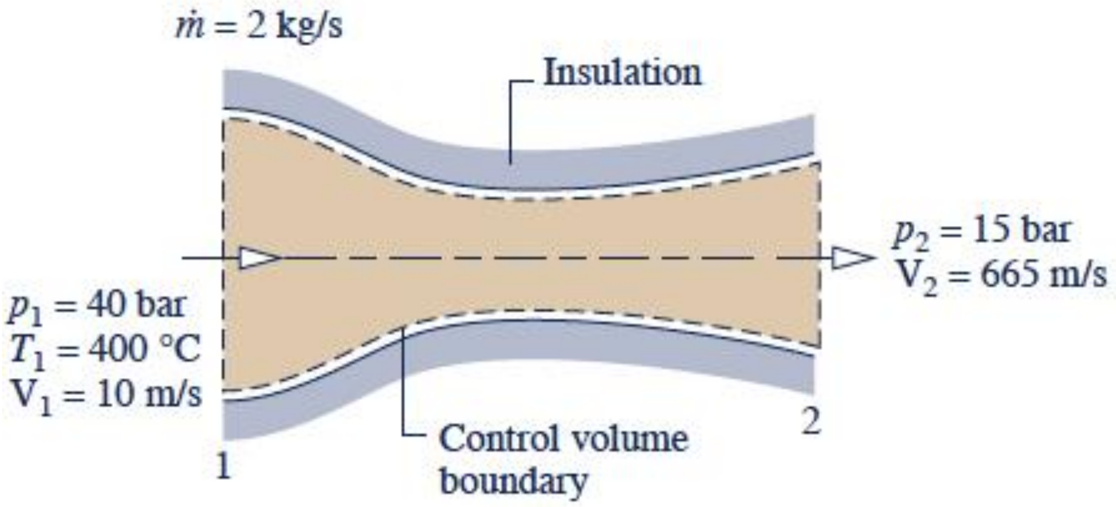
Steam enters a converging-diverging nozzle reaching a steady state

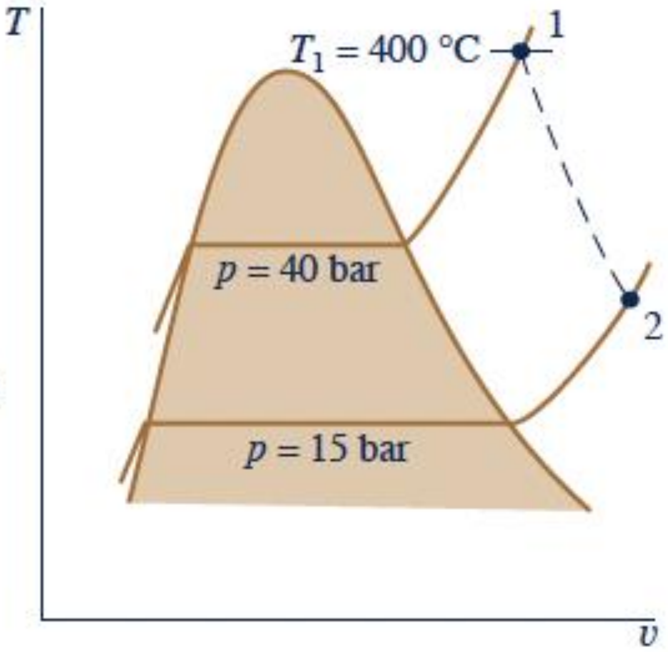
Heat transfer is negligible with the surrounding

Potential energy change can be neglected

Determine the exit area

Example: Steam Nozzle





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

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

With h_2 and p_2, we can find v_2 (specific volume)

$$A_2 = \frac{\dot{m}v_2}{|\vec{V}_2|}$$

Relation to Bernoulli's Principle

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

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

For incompressible fluids

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

$$u_1 + p_1 v_1 + \frac{\vec{V}_1^2}{2} + gz_1 = u_2 + p_2 v_2 + \frac{\vec{V}_2^2}{2} + gz_2$$

Incompressible substance, ignoring heat transfer/internal heat generation

$$du = c_v dT = \delta q = 0 \Rightarrow p_1 v_1 + \frac{\vec{V}_1^2}{2} + gz_1 = p_2 v_2 + \frac{\vec{V}_2^2}{2} + gz_2$$

Relation to Bernoulli's Principle

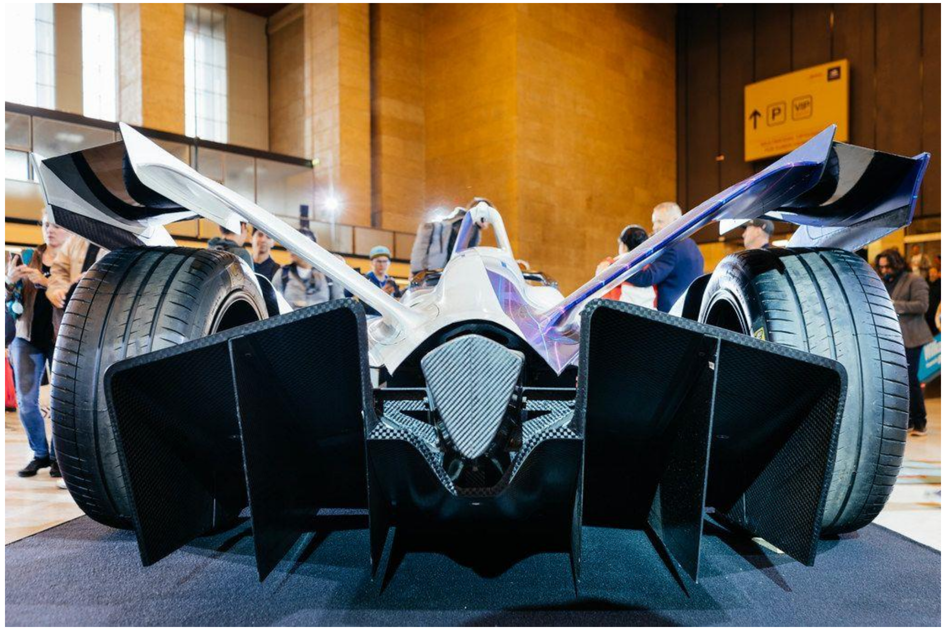
$$h_1 + \frac{\vec{V}_1^2}{2} + gz_1 = h_2 + \frac{\vec{V}_2^2}{2} + gz_2$$

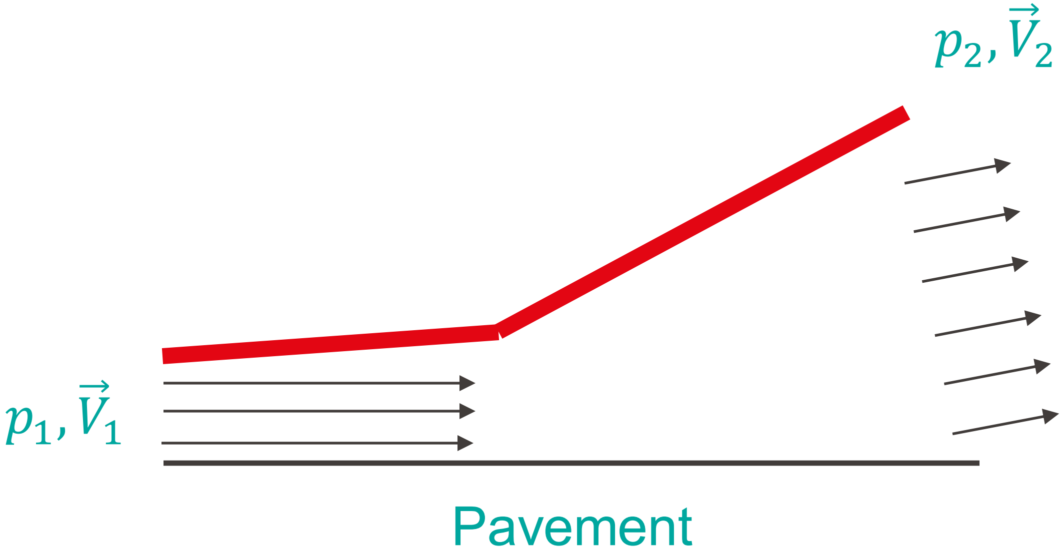
- For perfect gas, ignoring heat transfer

$$c_p(T_1 - T_2) + \frac{\vec{V}_1^2 - \vec{V}_2^2}{2} + gz_1 - gz_2 = 0$$

$$\frac{c_p}{R} pv + \frac{\vec{V}^2}{2} + gz = \text{const}$$

Race Car Diffuser



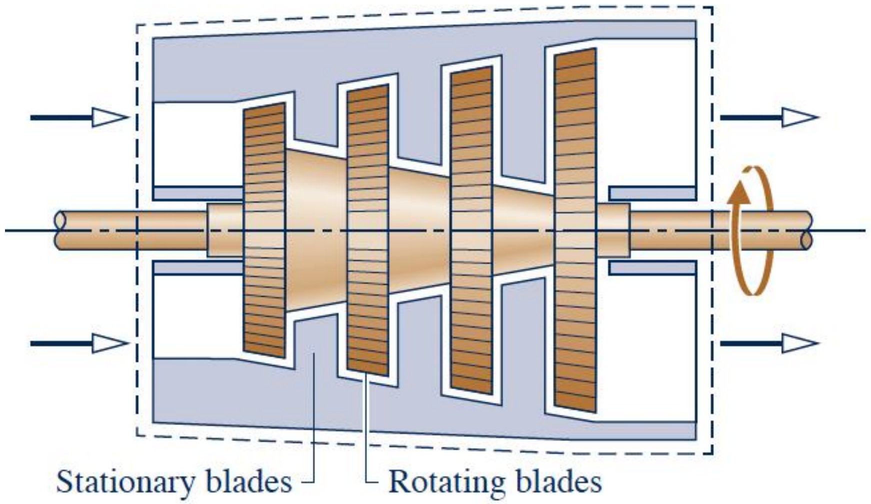


$$|\vec{V}_1| > |\vec{V}_2| \Rightarrow p_1 < p_2 \approx p_{atm}$$

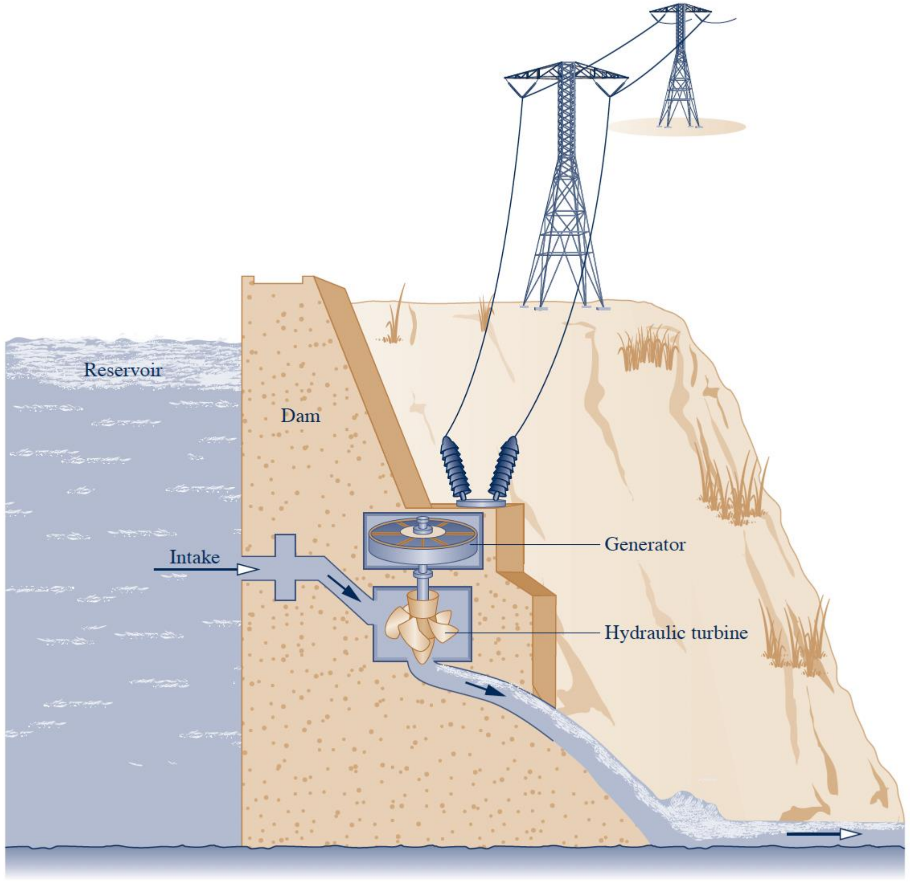
Aerodynamic grip

Turbine

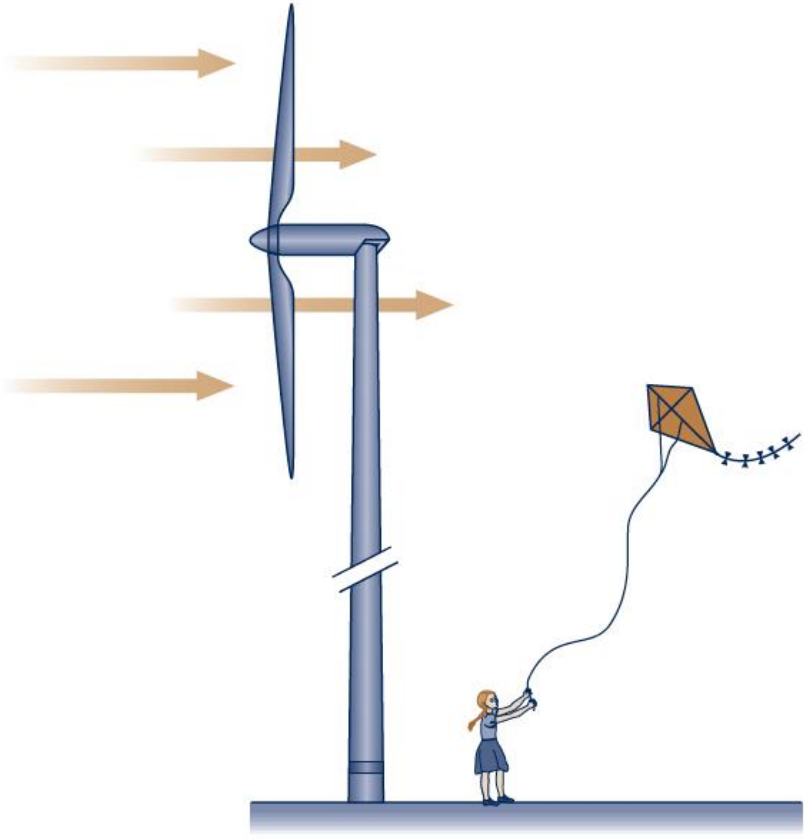
- A **turbine** is a device in which power is developed as a result of a gas or liquid passing through a set of blades attached to a shaft free to rotate



Turbine



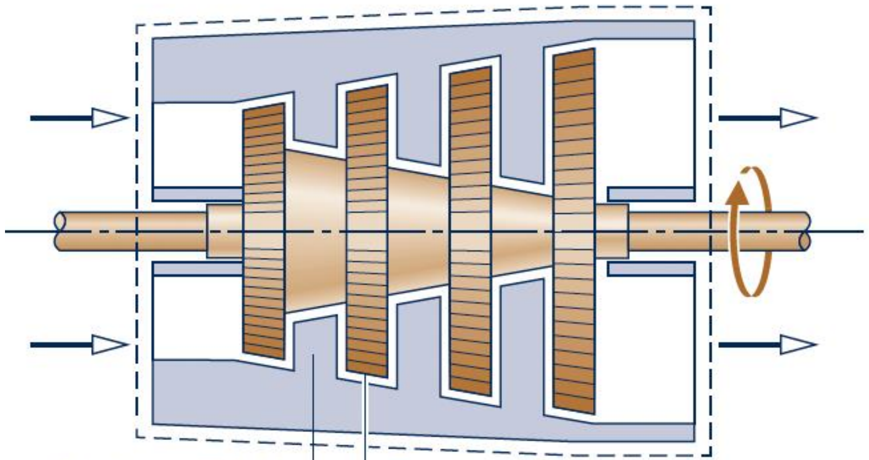
Hydraulic turbine



Wind turbine

Modeling Steam and Gas Turbine

Steady state



One inlet and one exit

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

Ignoring changes in kinetic and potential energy (assumption)

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

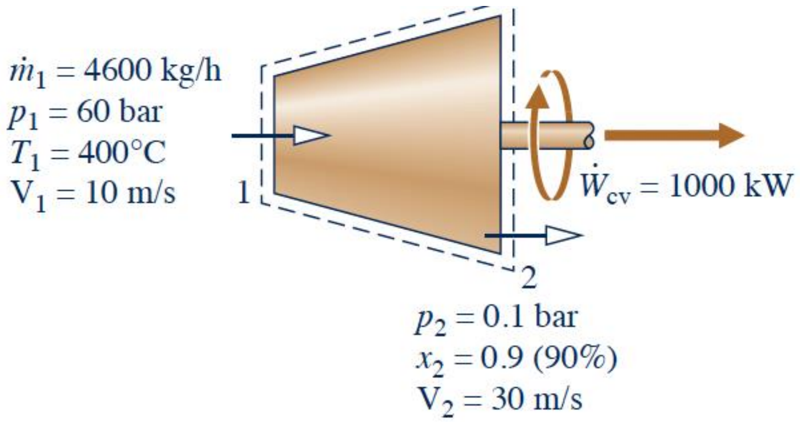
$$\dot{Q}_{cv} - \dot{W}_{cv} + \dot{m}(h_1 - h_2) = 0$$

Further ignoring heat transfer with the surrounding (assumption)

$$\dot{W}_{cv} = \dot{m}(h_1 - h_2)$$

$\dot{W}_{cv}$: turbine power output

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

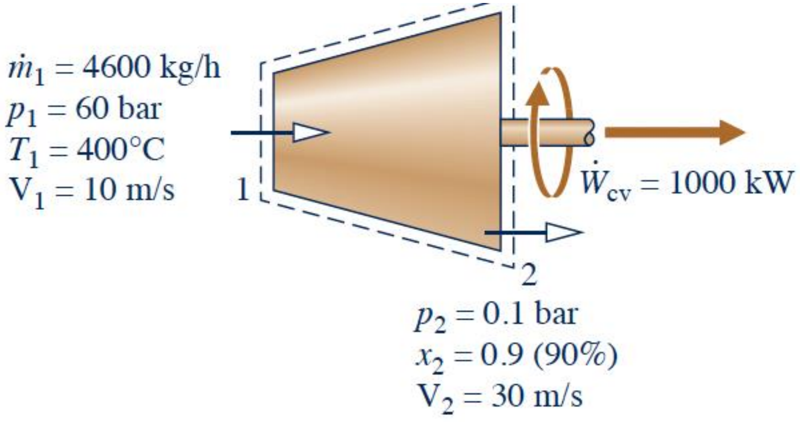
Ignore changes in potential energy

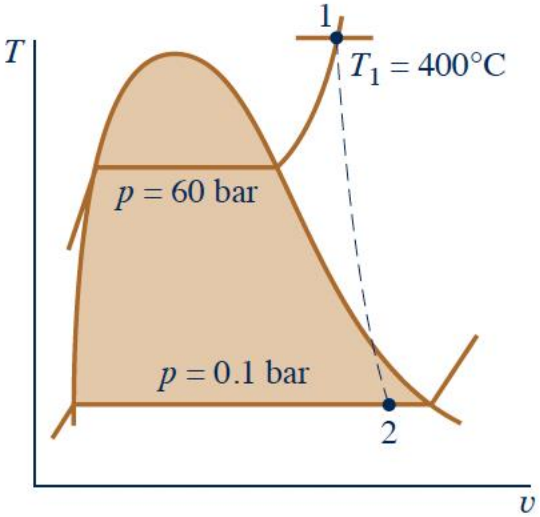
Calculate the rate of heat transfer

Define a control volume (dashed box)

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

Moran Example 4.4





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

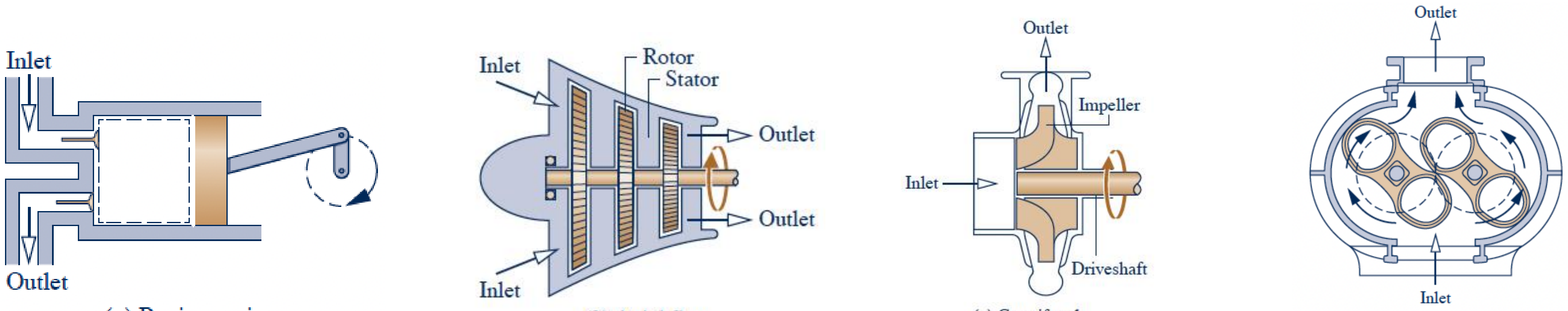
? ✓ ✓ ✓

From steam database, we can find state 1 is superheated vapor, thus from p_1 and T_1, we can find h_1

$h_2 = h_{f2} + x_2(h_{g2} - h_{f2})$ evaluated at p_2

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

Steady state, one inlet one exit

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

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

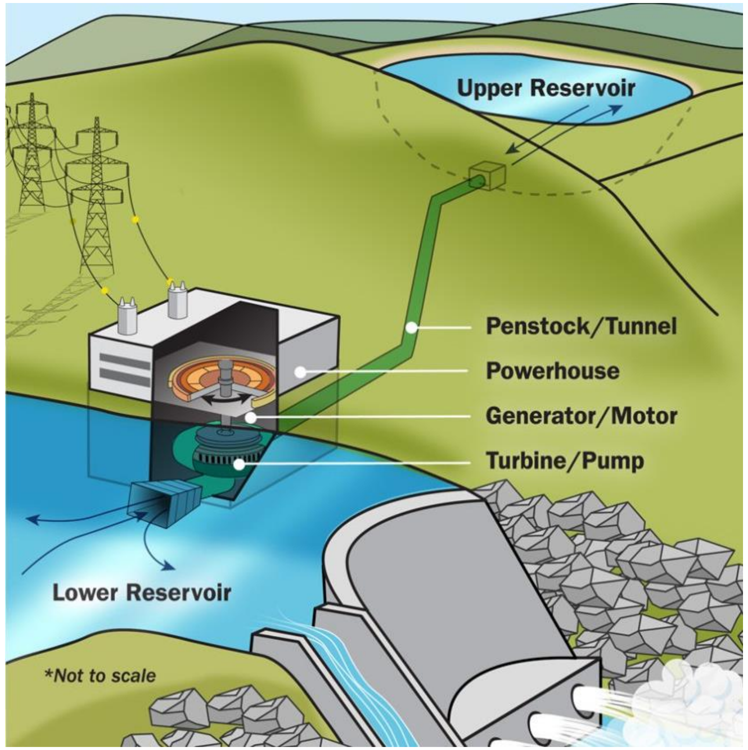
$$\dot{Q}_{cv} - \dot{W}_{cv} + \dot{m}(h_1 - h_2) = 0$$

Neglecting heat transfer (assumption), $\dot{W}_{cv} = \dot{m}(h_1 - h_2)$

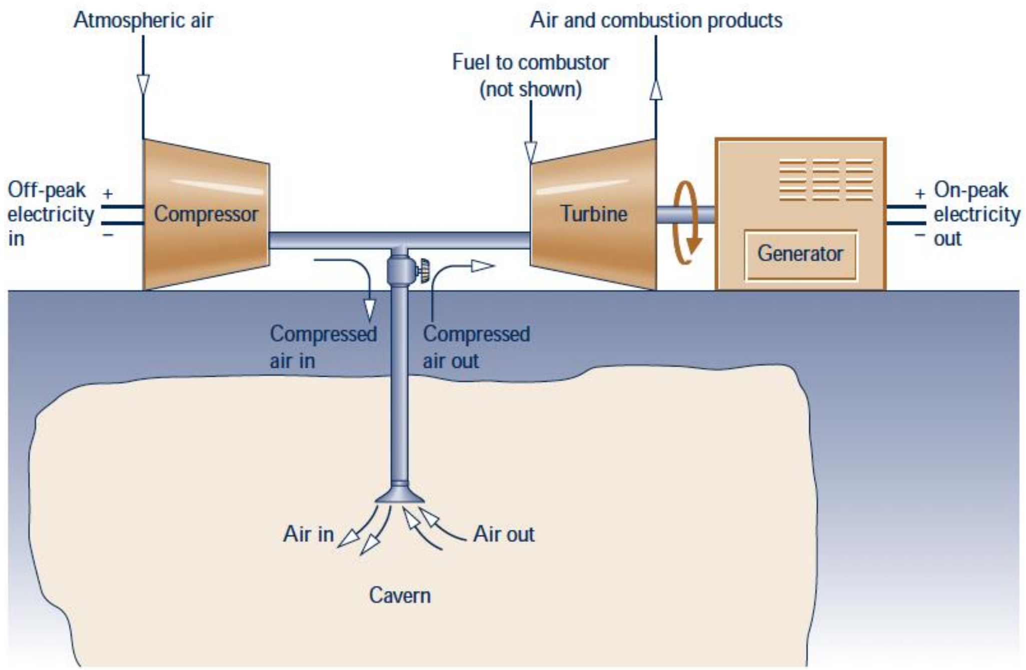
For pumps (liquid), the change in kinetic and potential energies are often significant

For both pumps and compressors, $\dot{W}_{cv} < 0$

Pumped-Hydro and Compressed-Air Energy Storage



Pump-hydro storage



Compressed-air storage