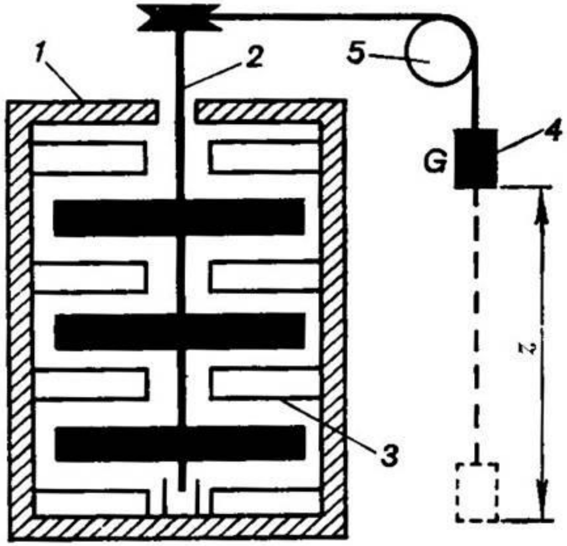
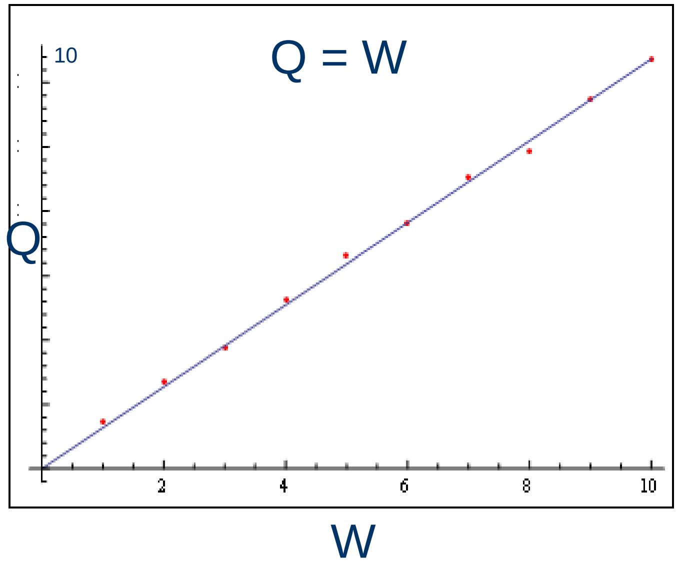
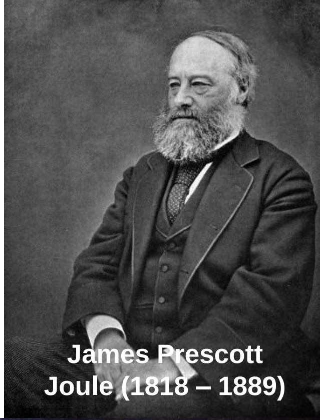
Joule’s Experiment





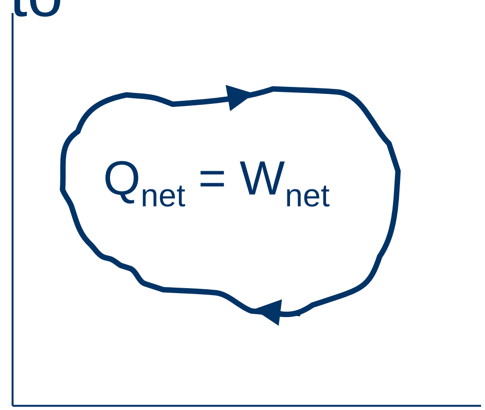


First law of thermodynamics

- When a closed system executes a complete cycle the sum of heat interactions is equal to the sum of work interactions

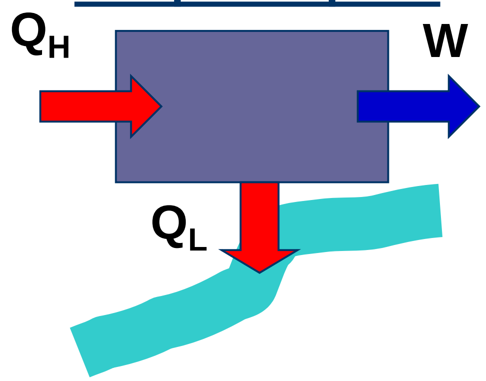
$$\oint \delta W = \oint \delta Q$$

$$\sum \delta W = \sum \delta Q$$



A cyclic process

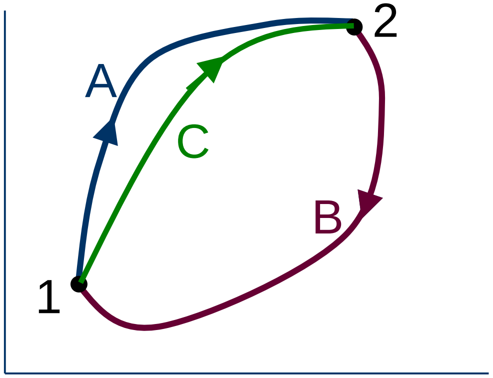
In a power plant



$Q_H - Q_L = W$

The difference (δQ – δW)

$$\oint(\delta Q-\delta W)=0$$



For cycle 1A2B1

I $$\int_{1A}^{2}(\delta Q-\delta W)+\int_{2B}^{1}(\delta Q-\delta W)=0$$

For cycle 1C2B1

II $$\int_{1C}^{2}(\delta Q-\delta W)+\int_{2B}^{1}(\delta Q-\delta W)=0$$

I– II $$\int_{1A}^{2}(\delta Q-\delta W)=\int_{1C}^{2}(\delta Q-\delta W)$$

Therefore, the integral $\int_{1}^{2}(\delta Q-\delta W)$ does not depend on path

The point function

- Therefore, (δQ – δW) is a point function:

$$\left(\delta Q - \delta W\right) = dE$$

- E is a property!! (but Q or W are not)
- E = stored total energy = me
- $e=(u+{}^{1}/_{2}\ C^{2}+ gz)$
- u = specific internal energy

Heat transfer – Work done = Change of total stored energy

$$\begin{bmatrix} \textit{change} \text{ in the amount} \\ \text{of energy contained} \\ \text{within the system} \\ \text{during some time} \\ \text{interval} \end{bmatrix} = \begin{bmatrix} \textit{net} \text{ amount of energy} \\ \text{transferred } \textit{in} \text{ across} \\ \text{the system boundary by} \\ \textit{heat} \text{ transfer during} \\ \text{the time interval} \end{bmatrix} - \begin{bmatrix} \textit{net} \text{ amount of energy} \\ \text{transferred } \textit{out} \text{ across} \\ \text{the system boundary} \\ \text{by } \textit{work} \text{ during the} \\ \text{time interval} \end{bmatrix}$$

First law for a nonflow process

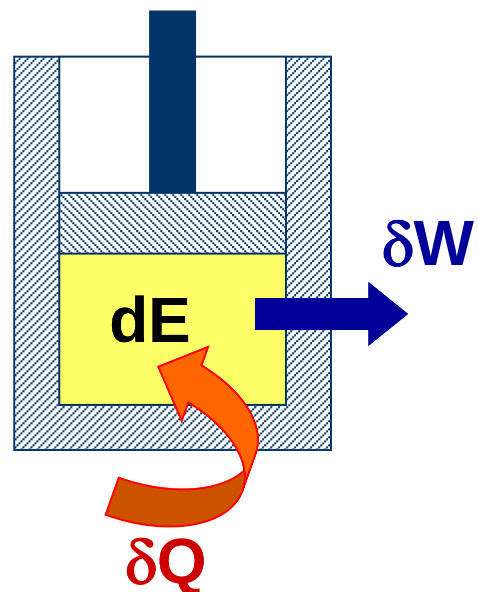
Heat transfer – Work done = Change of total stored energy

General $Q - W = \Delta E$

Stationary systems $Q - W = \Delta U$

Per unit mass $q - w = \Delta e$

Differential form $\delta q - \delta w = de$



$$\frac{dE}{dt} = \dot{Q} - \dot{W}$$

Example

- A closed system is taken through four processes constituting a power cycle. The measured work and heat interactions are described in the table below. Complete the missing measurements and determine the thermal efficiency of the cycle.

Process	W (kJ)	Q (kJ)	ΔU (kJ)
1 – 2	200	100	
2 – 3	100		100
3 – 4	–150		
4 – 1	50	0	

Concept of specific heats

- Specific heat at constant volume

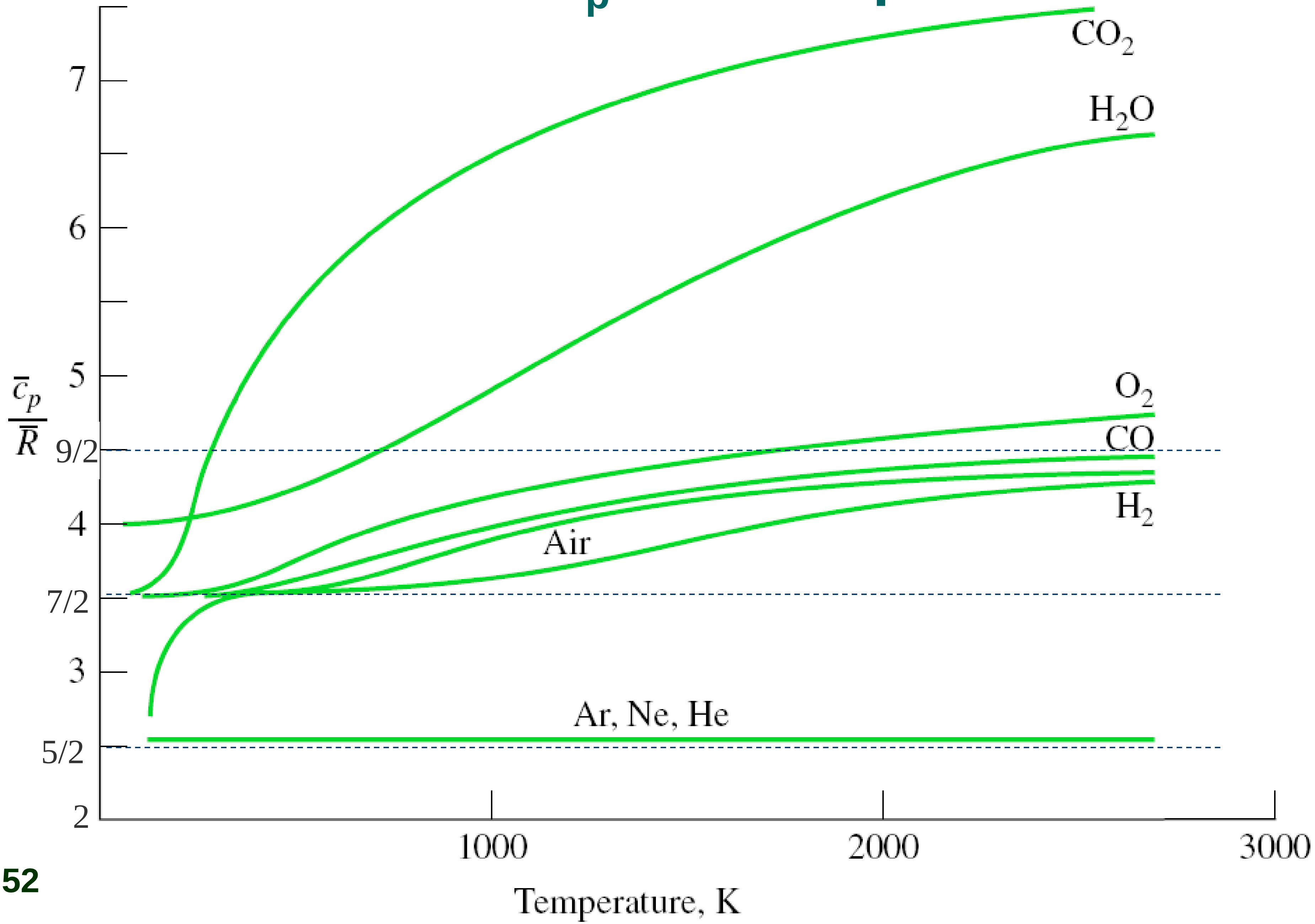
$$C_\upsilon = \frac{1}{m}\left(\frac{\delta Q}{\partial T}\right)\bigg|_\upsilon = \left(\frac{\partial u + \delta w}{\partial T}\right)\bigg|_\upsilon = \left(\frac{\partial u}{\partial T}\right)\bigg|_\upsilon$$

- Specific heat at constant pressure

$$C_p = \frac{1}{m}\left(\frac{\delta Q}{\partial T}\right)\bigg|_p = \left(\frac{\partial\left(u + p\upsilon\right)}{\partial T}\right)\bigg|_p = \left(\frac{\partial h}{\partial T}\right)\bigg|_p$$

  – For ideal gases, C_p and C_v are functions of T only

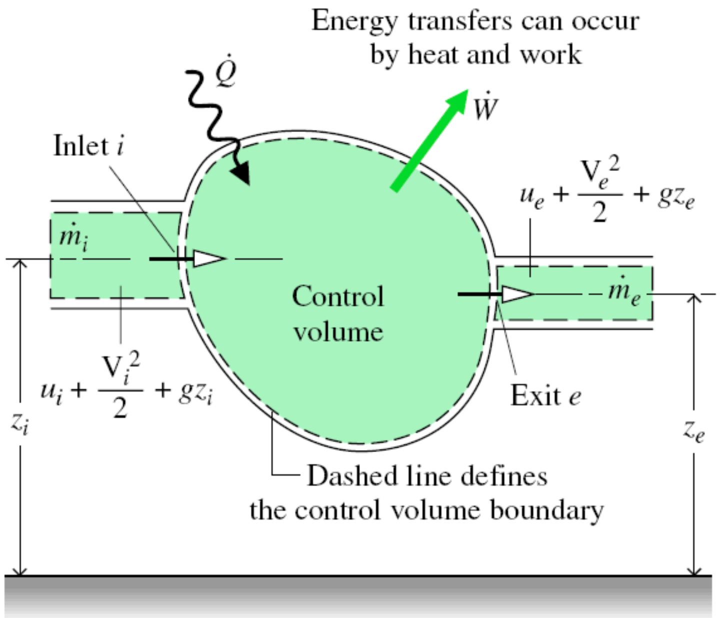
Variation of C_p with temperature



Steps to a problem analysis

- Identify the control mass and the control surface.
  - Draw the system showing all the heat and work interactions
  - Identify the δQ and δW and make sure their signs are correctly chosen w.r.t. the control surface
- Identify the properties that are known (e.g., the initial and final states)
- What is the process that the system undergoes?
- Draw p-v or T-s diagrams
- Identify the governing principle that applies (e.g., Conservation of mass, 1st Law or 2nd Law)
- Solve

First law for an open system



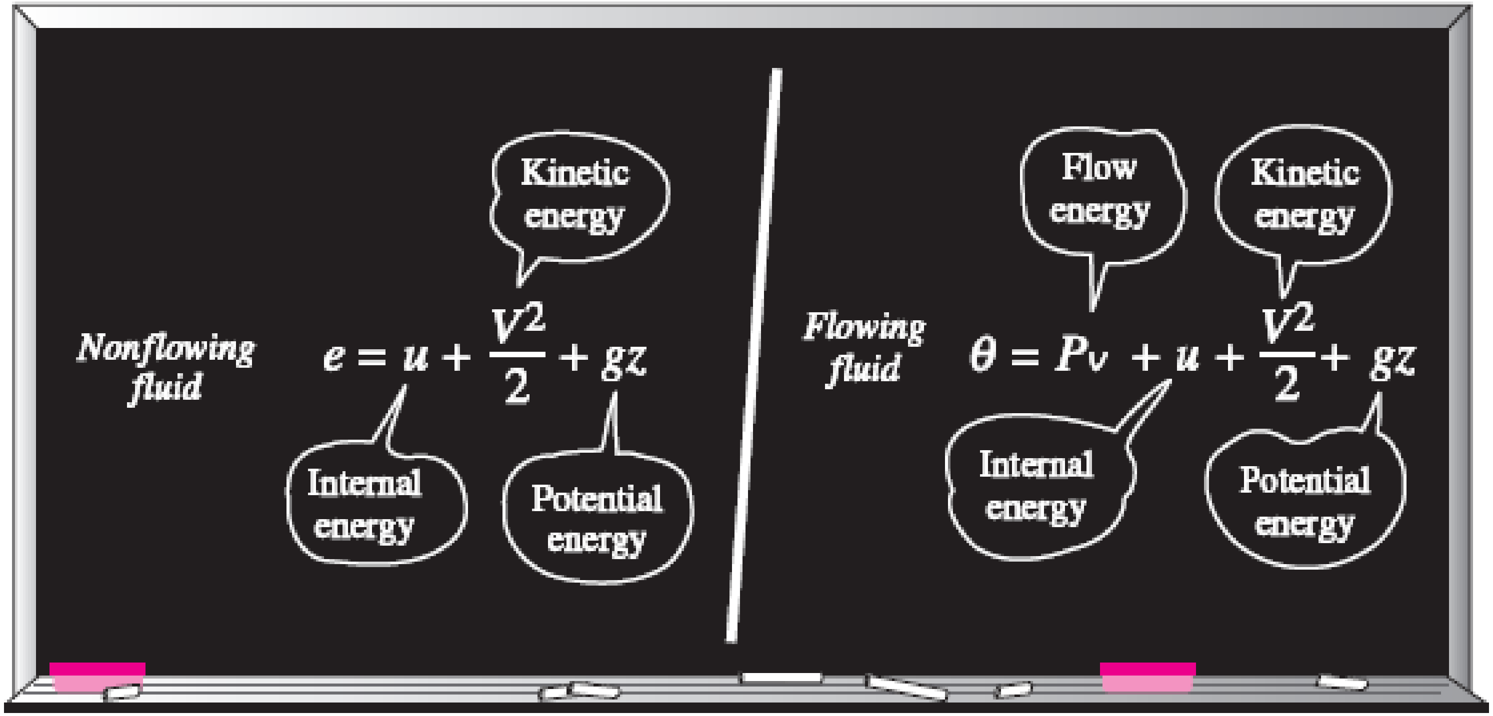
$$\begin{bmatrix}\text{time } \textit{rate of change} \\ \text{of the energy} \\ \text{contained within} \\ \text{the control volume } \textit{at} \\ \textit{time } t\end{bmatrix} = \begin{bmatrix}\text{net } \textit{rate} \text{ at which} \\ \text{energy is being} \\ \text{transferred in} \\ \text{by heat transfer} \\ \textit{at time } t\end{bmatrix} - \begin{bmatrix}\text{net } \textit{rate} \text{ at which} \\ \text{energy is being} \\ \text{transferred out} \\ \text{by work } \textit{at} \\ \textit{time } t\end{bmatrix} + \begin{bmatrix}\textit{net} \text{ rate of energy} \\ \text{transfer } \textit{into} \text{ the} \\ \text{control volume} \\ \text{accompanying} \\ \text{mass flow}\end{bmatrix}$$

$$\frac{dE_{\text{cv}}}{dt} = \dot{Q} - \dot{W} + \dot{m}_i\left(u_i + \frac{V_i^2}{2} + gz_i\right) - \dot{m}_e\left(u_e + \frac{V_e^2}{2} + gz_e\right)$$

$$\dot{W} = \dot{W}_{\text{cv}} + \dot{m}_e(p_e v_e) - \dot{m}_i(p_i v_i)$$

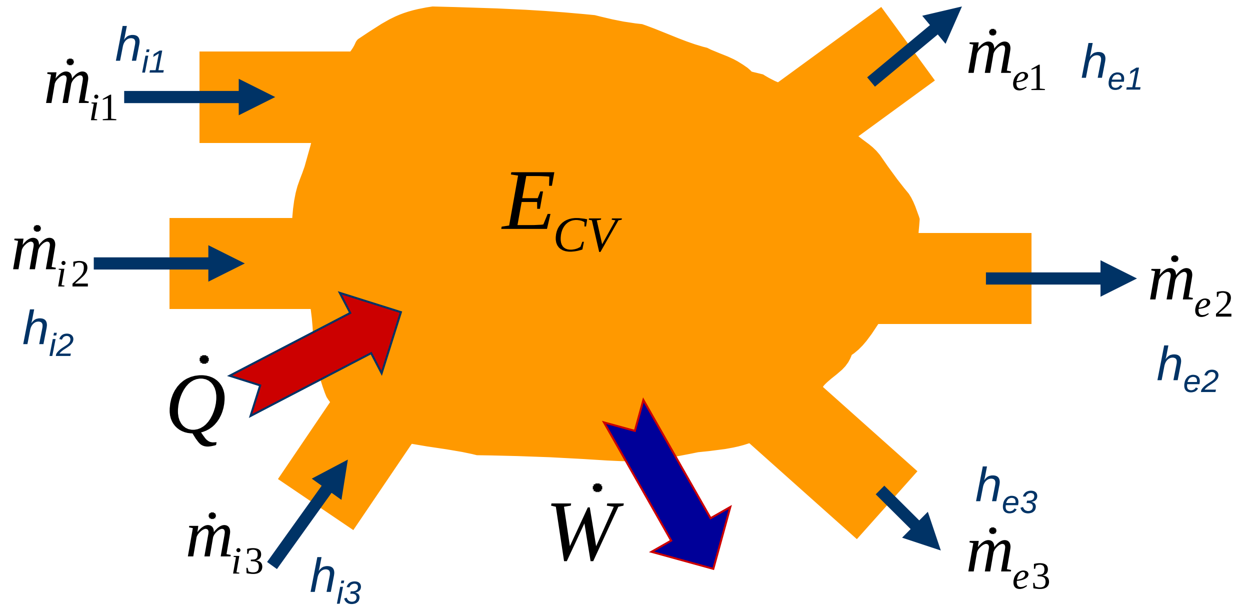
$$\frac{dE_{\text{cv}}}{dt} = \dot{Q}_{\text{cv}} - \dot{W}_{\text{cv}} + \dot{m}_i\left(h_i + \frac{V_i^2}{2} + gz_i\right) - \dot{m}_e\left(h_e + \frac{V_e^2}{2} + gz_e\right)$$

Energy associated with flowing and nonflowing fluids



Non flowing Fluid: e.g., gas in a closed container that is travelling at speed V
Flowing Fluid: e.g., gas entering or leaving a control volume at a speed V

Multi-inlet & multi-exit control volume



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

Steady flow energy equation

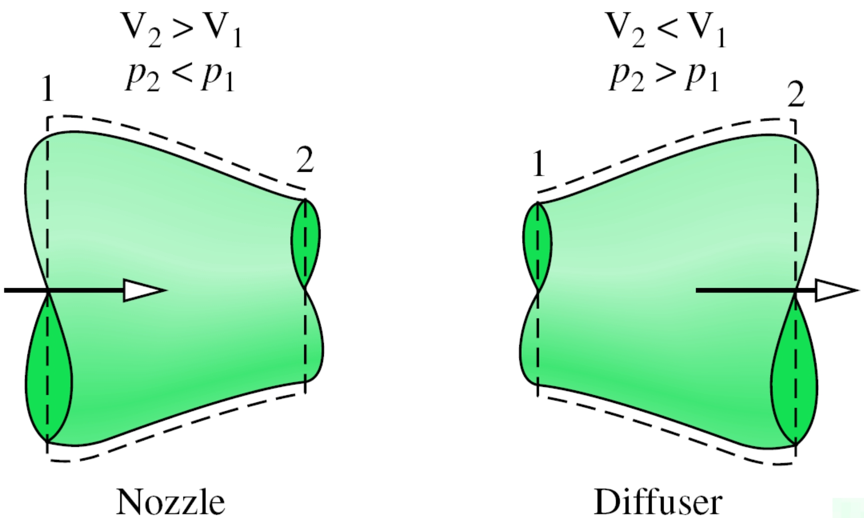
0

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

$$\underbrace{\dot{Q}_{cv} + \sum_i \dot{m}_i \left(h_i + \frac{V_i^2}{2} + gz_i \right)}_{\text{(energy rate in)}} = \underbrace{\dot{W}_{cv} + \sum_e \dot{m}_e \left(h_e + \frac{V_e^2}{2} + gz_e \right)}_{\text{(energy rate out)}}$$

Steady flow devices

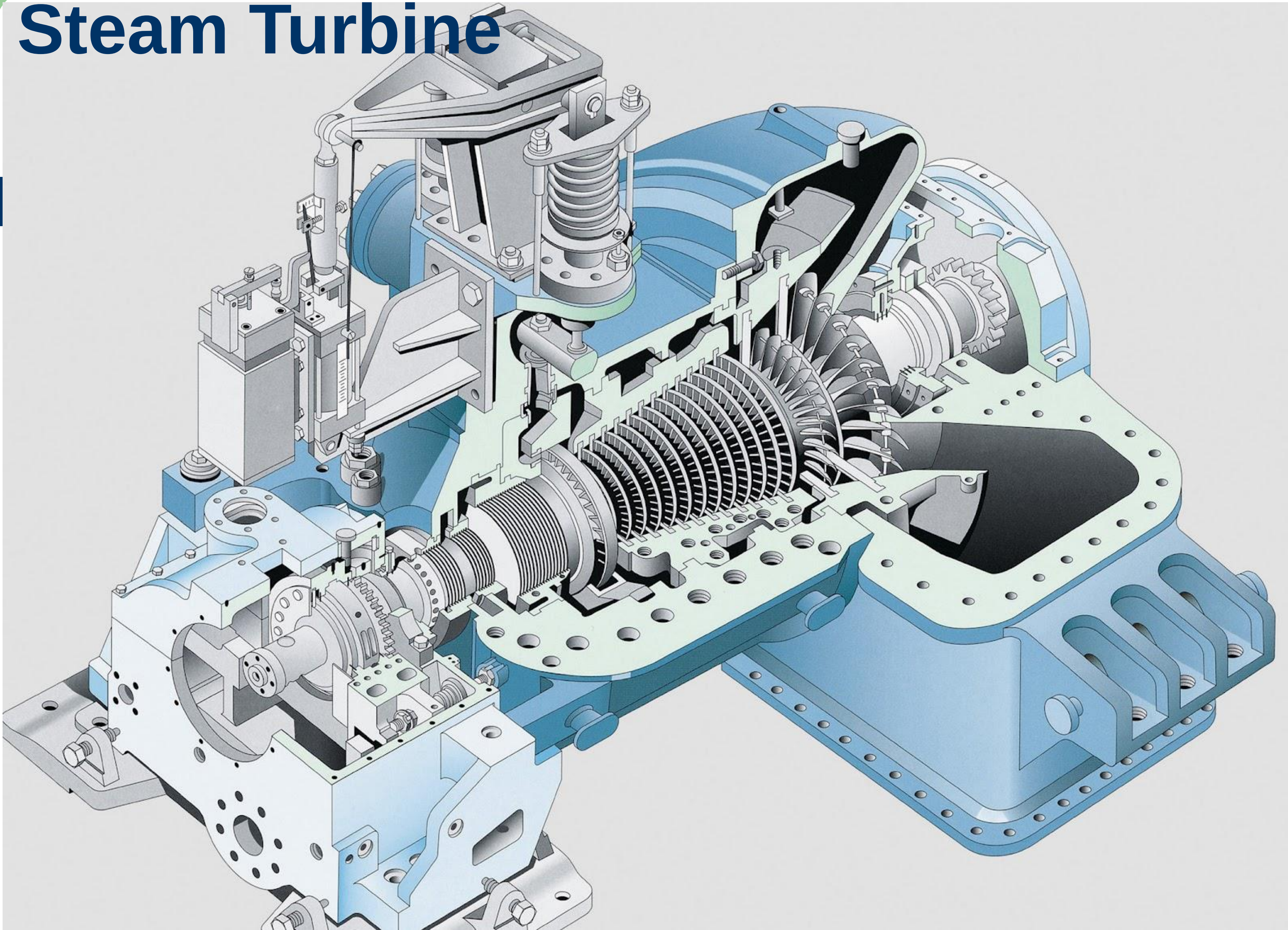
- **Nozzles and diffusers**



- No heat transfer
- No work done
- Enthalpy is converted to kinetic energy (in a nozzle), or vice versa (in a diffuser)

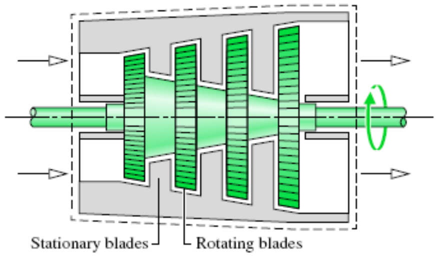
$$\dot{Q} = 0; \quad \dot{W} = 0 \quad \Rightarrow \quad h_2 = h_1 + \left(\frac{V_1^2 - V_2^2}{2}\right)$$

Steam Turbine



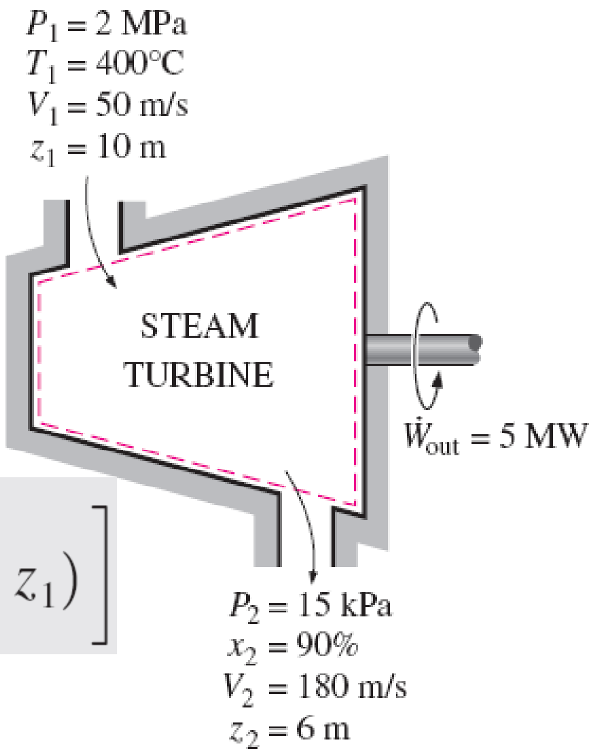
$$\dot{Q}_{cv} + \sum_i \dot{m}_i\left(h_i + \frac{V_i^2}{2} + gz_i\right) = \dot{W}_{cv} + \sum_e \dot{m}_e\left(h_e + \frac{V_e^2}{2} + gz_e\right)$$

(energy rate in) (energy rate out)



Steady flow devices (contd…)

- **Turbine**
  - No heat transfer (adiabatic)
  - Enthalpy converts to work



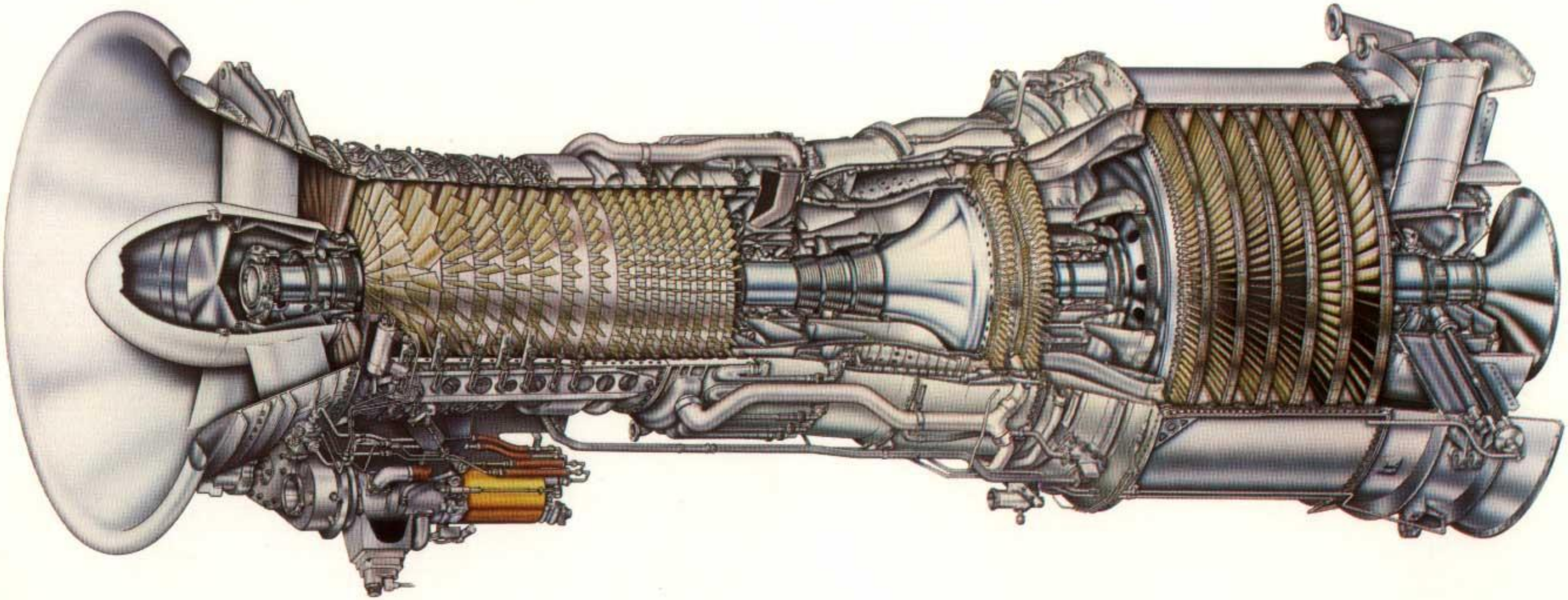
$$\dot{m}\left(h_1 + \frac{V_1^2}{2} + gz_1\right) = \dot{W}_{out} + \dot{m}\left(h_2 + \frac{V_2^2}{2} + gz_2\right)$$

$$w_{out} = -\left[(h_2 - h_1) + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)\right]$$

When the change of kinetic and potential energies neglected,

$$w_{out} = (h_1 - h_2)$$

Gas Turbine and Compressor



General Electric LM2500 Gas Turbine

$$\dot{Q}_{cv} + \sum_i \dot{m}_i\left(h_i + \frac{V_i^2}{2} + gz_i\right) = \dot{W}_{cv} + \sum_e \dot{m}_e\left(h_e + \frac{V_e^2}{2} + gz_e\right)$$

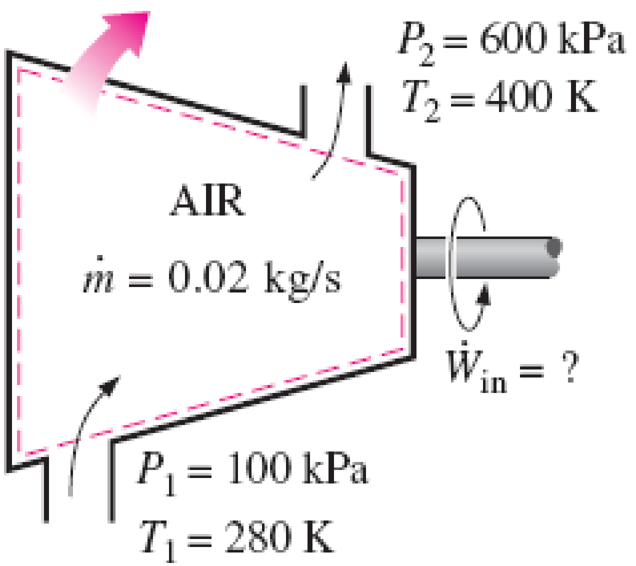
(energy rate in) (energy rate out)

Steady flow devices (contd…)

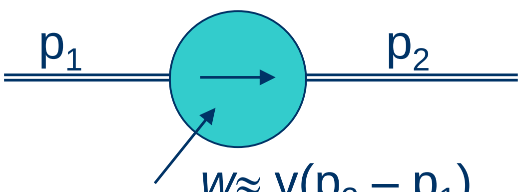
- **Compressor**
  - Work converts to enthalpy
  - $\Delta ke \approx 0; \Delta pe \approx 0$

$$\dot{W}_{in} = \dot{m}q_{out} + \dot{m}(h_2 - h_1)$$

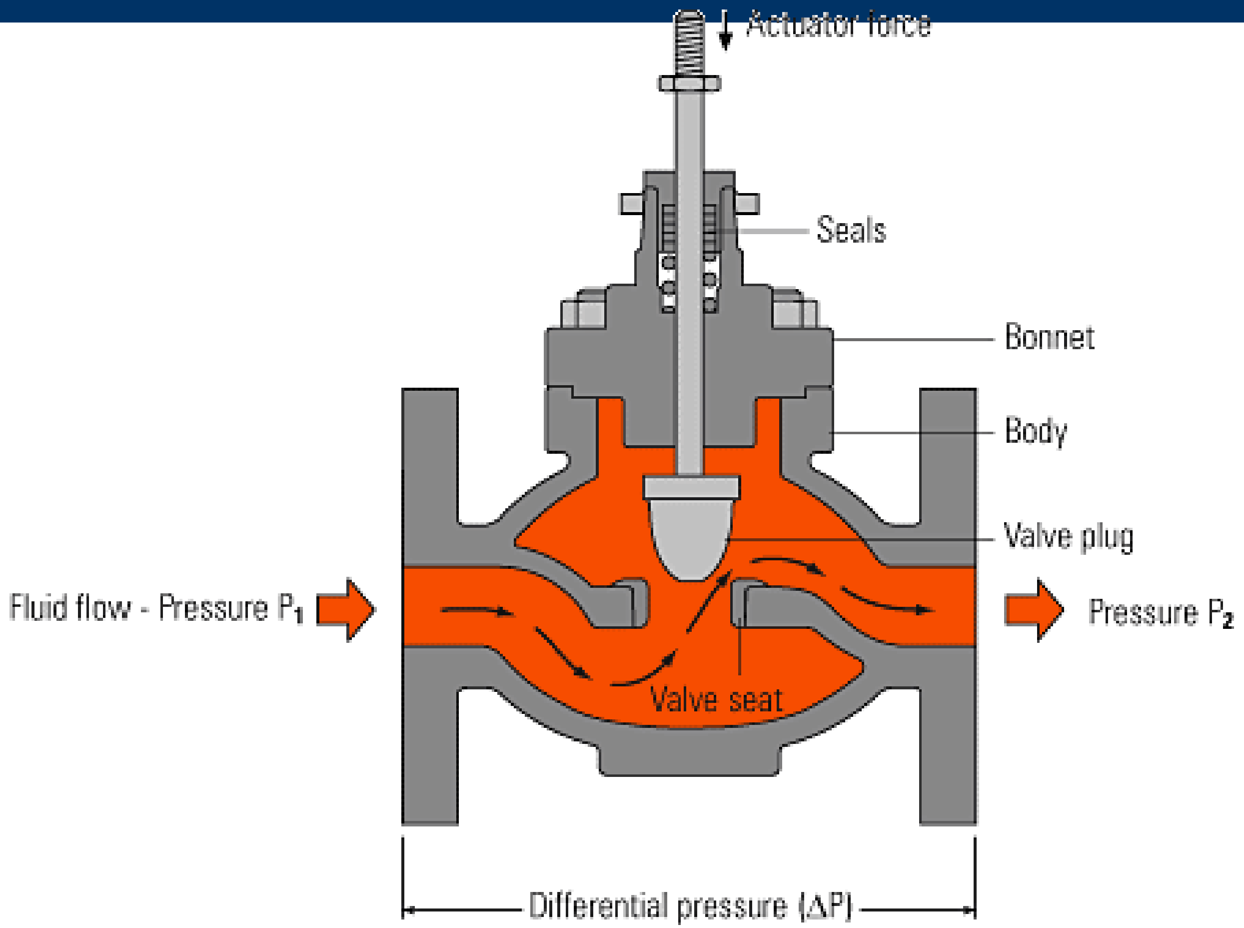
  - Work is consumed



- **Pump**
  - Work converts to enthalpy
  - $\Delta ke \approx 0; \Delta pe \approx 0, q \approx 0$
  - $w_{pump} = -\int v\,dp \approx -v\,\Delta p$



Throttling in a control valve

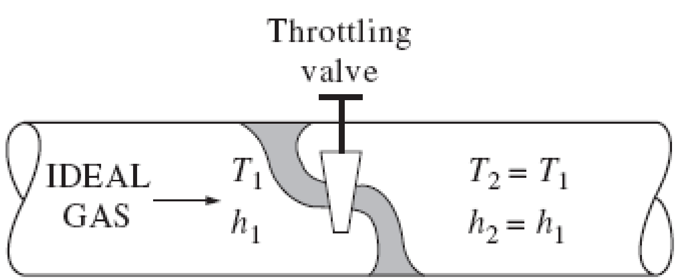


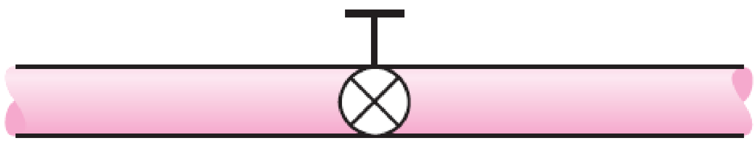
$$\dot{Q}_{cv} + \sum_i \dot{m}_i\left(h_i + \frac{V_i^2}{2} + gz_i\right) = \dot{W}_{cv} + \sum_e \dot{m}_e\left(h_e + \frac{V_e^2}{2} + gz_e\right)$$

(energy rate in) (energy rate out)

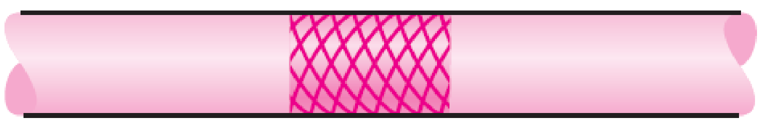
Steady flow devices (contd…)

- **Throttling**
  - No work done
  - No heat transfer
  - $\Delta ke \approx 0$; $\Delta pe \approx 0$
  - $h_1 = h_2$





(*a*) An adjustable valve



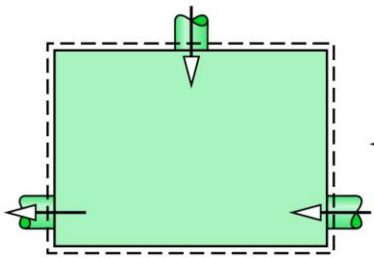
(*b*) A porous plug

(*c*) A capillary tube

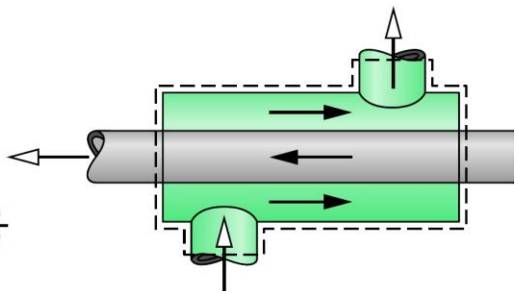
$$\dot{Q}_{cv} + \sum_i \dot{m}_i\left(h_i + \frac{V_i^2}{2} + gz_i\right) = \dot{W}_{cv} + \sum_e \dot{m}_e\left(h_e + \frac{V_e^2}{2} + gz_e\right)$$

(energy rate in) (energy rate out)

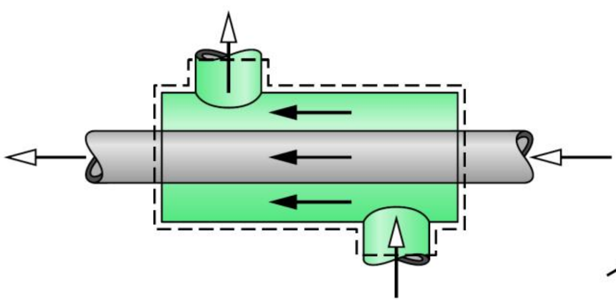
Steady flow devices (contd…)



Direct contact type



Surface type, parallel flow



Surface type, counter flow

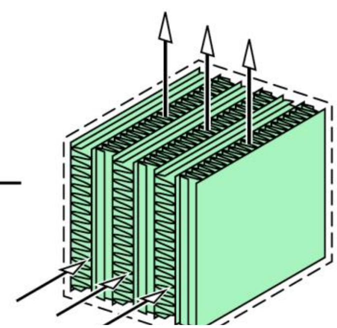
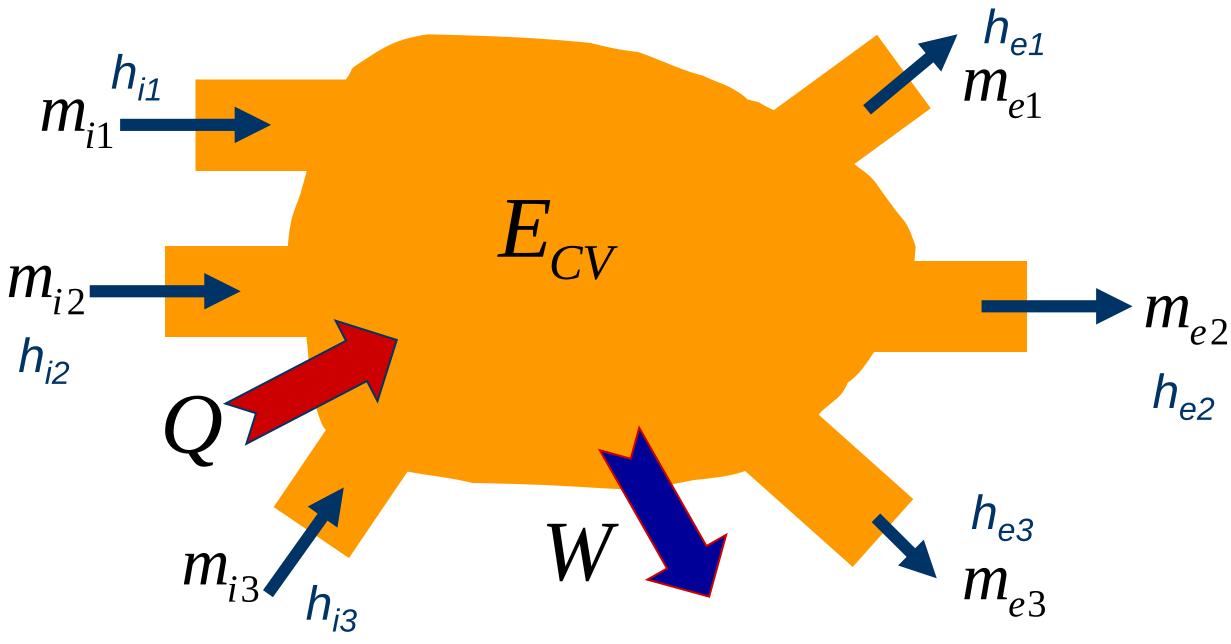


Plate type, cross flow

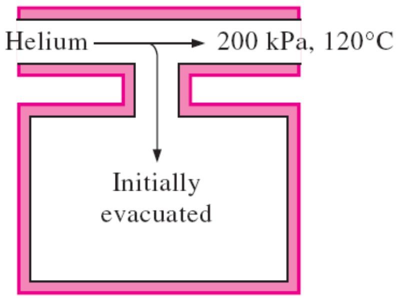
- **Heat exchangers**
  - No work done
  - No heat transfer across the control surface
    - Energy transfer from one fluid to the other within the CV takes place
  - $\Delta ke \approx 0; \Delta pe \approx 0$
  - $\Sigma h_{in} = \Sigma h_{out}$

Unsteady flow problem



$$\left(E_2 - E_1\right) = Q - W + \int \left(h_i + \frac{1}{2} C_i^2 + g z_i \right) dm_i - \int \left(h_e + \frac{1}{2} C_e^2 + g z_e \right) dm_e$$

Filling of an empty cylinder



5–124 A rigid, insulated tank that is initially evacuated is connected through a valve to a supply line that carries helium at 200 kPa and 120°C. Now the valve is opened, and helium is allowed to flow into the tank until the pressure reaches 200 kPa, at which point the valve is closed. Determine the flow work of the helium in the supply line and the final temperature of the helium in the tank. *Answers:* 816 kJ/kg, 655 K