ESO 201A: Thermodynamics

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Mass-Energy Analysis: part 2

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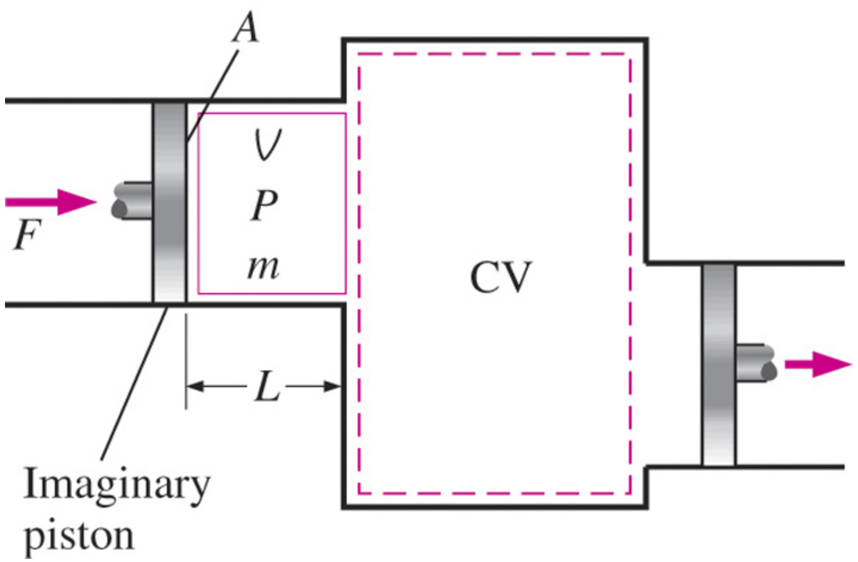
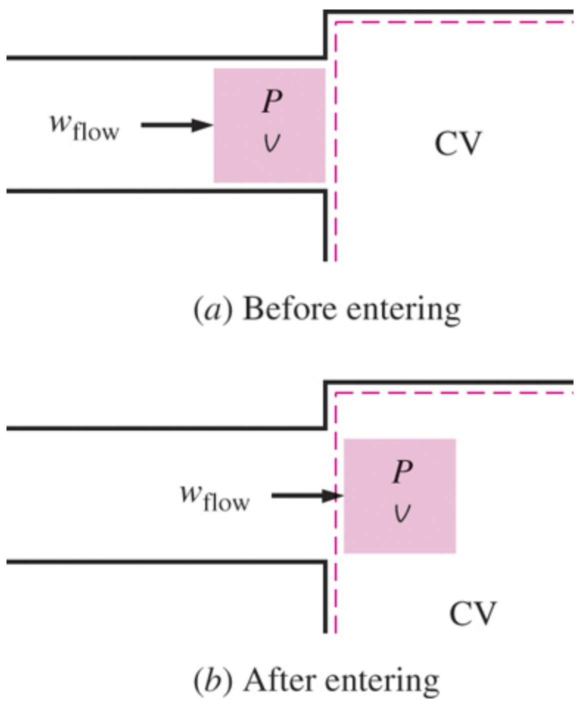
Learning objectives

- Develop the conservation of mass principle.
- Apply the conservation of mass principle to various systems including steady- and unsteady-flow control volumes.
- Apply the first law of thermodynamics as the statement of the conservation of energy principle to control volumes.
- Identify the energy carried by a fluid stream crossing a control surface as the sum of internal energy, flow work, kinetic energy, and potential energy of the fluid and to relate the combination of the internal energy and the flow work to the property enthalpy.
- Solve energy balance problems for common steady-flow devices such as nozzles, compressors, turbines, throttling valves, mixers, heaters, and heat exchangers.
- Apply the energy balance to general unsteady-flow processes with particular emphasis on the uniform-flow process as the model for commonly encountered charging and discharging processes.

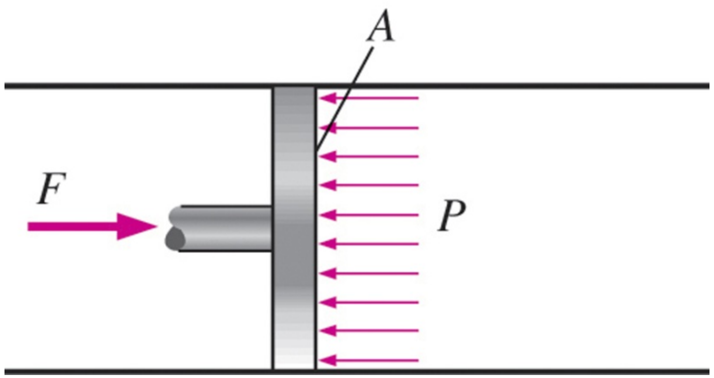
Flow work and Energy of Flowing Fluid

Flow work, or flow energy: The work (or energy) required to push the mass into or out of the control volume. This work is necessary for maintaining a continuous flow through a control volume.





Flow work



$$F = PA$$

In the absence of acceleration, the force applied on a fluid by a piston is equal to the force applied on the piston by the fluid.

$$W_{\text{flow}} = FL = PAL = PV \qquad (\text{kJ})$$

$$w_{\text{flow}} = Pv \qquad (\text{kJ/kg})$$

Note: unlike other work quantities, flow work is a product of two properties of a fluid Thus viewed as a flow energy or transport energy!

Total Energy of Flowing Fluid

Total energy of a simple compressible system consists of three parts: internal, kinetic, and potential energies

$$e = u + \mathrm{ke} + \mathrm{pe} = u + \frac{V^2}{2} + gz \qquad \text{(kJ/kg)}$$

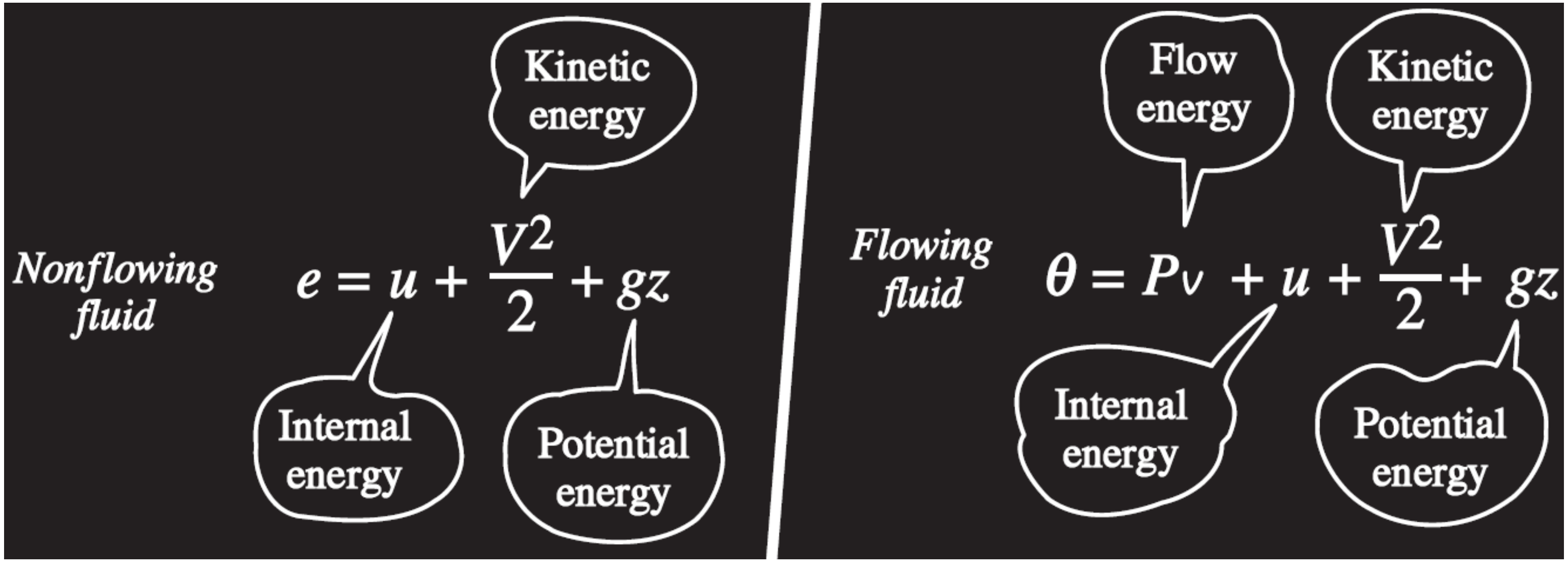
The fluid entering or leaving CV possess an additional form of energy- the flow energy Pv. Then the total energy of a flowing fluid

$$\theta = Pv + e = Pv + (u + \mathrm{ke} + \mathrm{pe})$$

$$\theta = h + \mathrm{ke} + \mathrm{pe} = h + \frac{V^2}{2} + gz \qquad \text{(kJ/kg)}$$

The flow energy is automatically taken care of by enthalpy. In fact, this is the main reason for defining the property enthalpy.

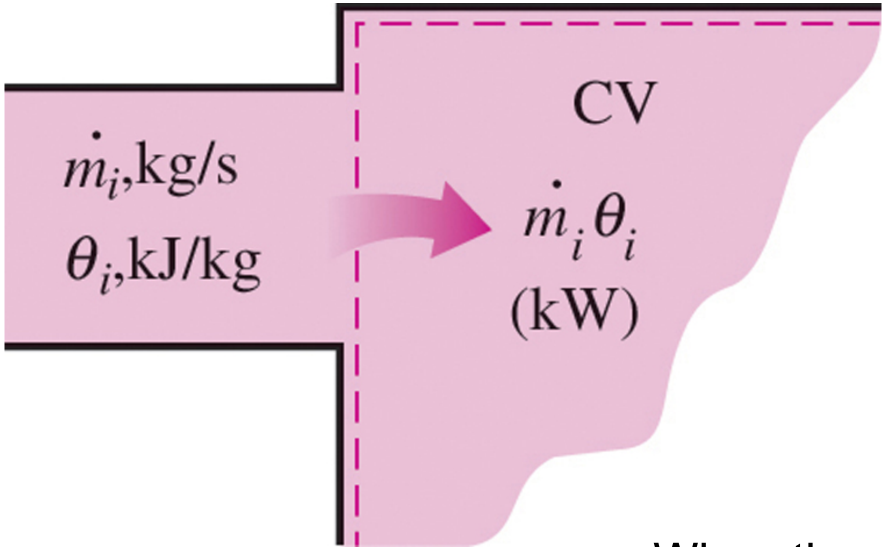
Total Energy of Flowing Fluid



The total energy consists of three parts for a nonflowing fluid and four parts for a flowing fluid.

Amount of energy transport: $E_{\text{mass}} = m\theta = m\left(h + \frac{V^2}{2} + gz\right)$ (kJ)

Rate of energy transport: $\dot{E}_{\text{mass}} = \dot{m}\theta = \dot{m}\left(h + \frac{V^2}{2} + gz\right)$ (kW)



When the kinetic and potential energies of a fluid stream are negligible

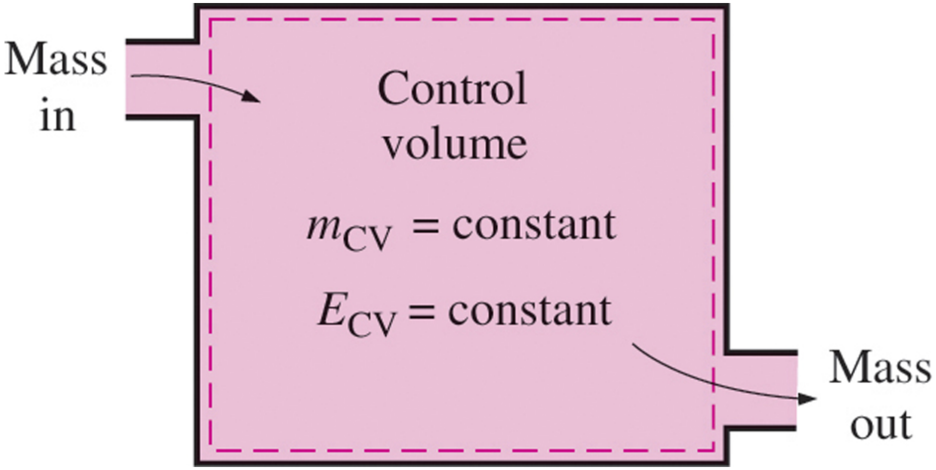
$$E_{\text{mass}} = mh \qquad \dot{E}_{\text{mass}} = \dot{m}h$$

When the properties of the mass at each inlet or exit change with time as well as over the cross section

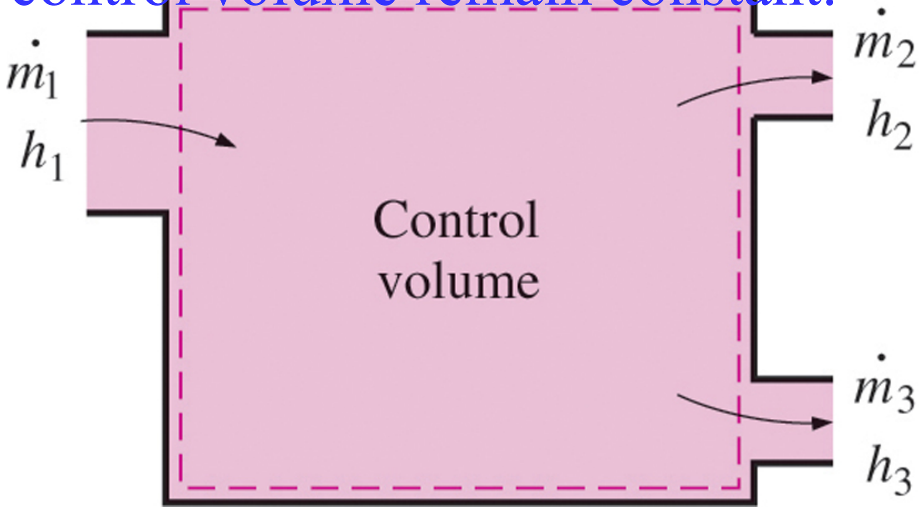
$$E_{\text{in,mass}} = \int_{m_i} \theta_i \, \delta m_i = \int_{m_i} \left(h_i + \frac{V_i^2}{2} + gz_i\right) \delta m_i$$

Energy analysis of steady flow system

Many engineering systems such as power plants operate under steady conditions.



Under steady-flow conditions, the mass and energy contents of a control volume remain constant.



Under steady-flow conditions, the fluid properties at an inlet or exit remain constant (do

Mass and Energy balances for a steady-flow process

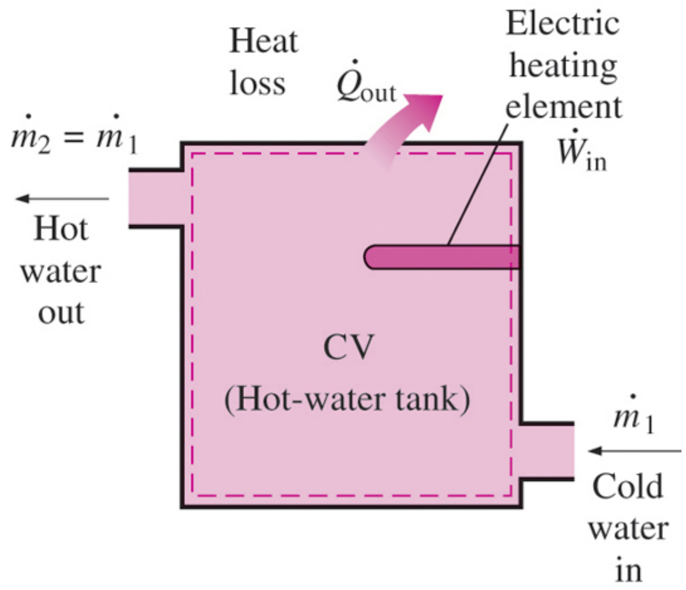
$$\sum_{\text{in}} \dot{m} = \sum_{\text{out}} \dot{m} \qquad (\text{kg/s})$$

$$\dot{m}_1 = \dot{m}_2$$

$$\rho_1 V_1 A_1 = \rho_2 V_2 A_2$$

Mass balance

A water heater in steady



Energy balance

$$\underbrace{\dot{E}_{\text{in}} - \dot{E}_{\text{out}}}_{\substack{\text{Rate of net energy transfer}\\ \text{by heat, work, and mass}}} = \underbrace{dE_{\text{system}}/dt \nearrow^{0\ (\text{steady})}}_{\substack{\text{Rate of change in internal, kinetic,}\\ \text{potential, etc., energies}}} = 0$$

$$\underbrace{\dot{E}_{\text{in}}}_{\substack{\text{Rate of net energy transfer in}\\ \text{by heat, work, and mass}}} = \underbrace{\dot{E}_{\text{out}}}_{\substack{\text{Rate of net energy transfer out}\\ \text{by heat, work, and mass}}} \qquad (\text{kW})$$

$$\dot{Q}_{\text{in}} + \dot{W}_{\text{in}} + \sum_{\text{in}} \underbrace{\dot{m}\left(h + \frac{V^2}{2} + gz\right)}_{\text{for each inlet}} = \dot{Q}_{\text{out}} + \dot{W}_{\text{out}} + \sum_{\text{out}} \underbrace{\dot{m}\left(h + \frac{V^2}{2} + gz\right)}_{\text{for each exit}}$$

Mass and Energy balances for a steady-flow process

Energy balance

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\substack{\text{Rate of net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{dE_{system}/dt \xrightarrow{} 0 \text{ (steady)}}_{\substack{\text{Rate of change in internal, kinetic,} \\ \text{potential, etc., energies}}} = 0$$

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$$\dot{Q}_{in} + \dot{W}_{in} + \sum_{in} \underbrace{\dot{m}\left(h + \frac{V^2}{2} + gz\right)}_{\text{for each inlet}} = \dot{Q}_{out} + \dot{W}_{out} + \sum_{out} \underbrace{\dot{m}\left(h + \frac{V^2}{2} + gz\right)}_{\text{for each exit}}$$

Useful when magnitude and directions of heat and work transfers are known!

Energy balance relations with sign conventions (i.e., heat input and work output are positive)

$$\dot{Q} - \dot{W} = \sum_{\text{out}} \underbrace{\dot{m}\left(h + \frac{V^2}{2} + gz\right)}_{\text{for each exit}} - - \sum_{\text{in}} \underbrace{\dot{m}\left(h + \frac{V^2}{2} + gz\right)}_{\text{for each inlet}}$$

Single stream

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

$$q - w = h_2 - h_1 + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)$$

$$q - w = h_2 - h_1 \qquad q = \dot{Q}/\dot{m} \quad w = \dot{W}/\dot{m}$$

Energy balance relations with sign conventions (i.e., heat input and work output are positive)

$$q - w = h_2 - h_1 + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)$$

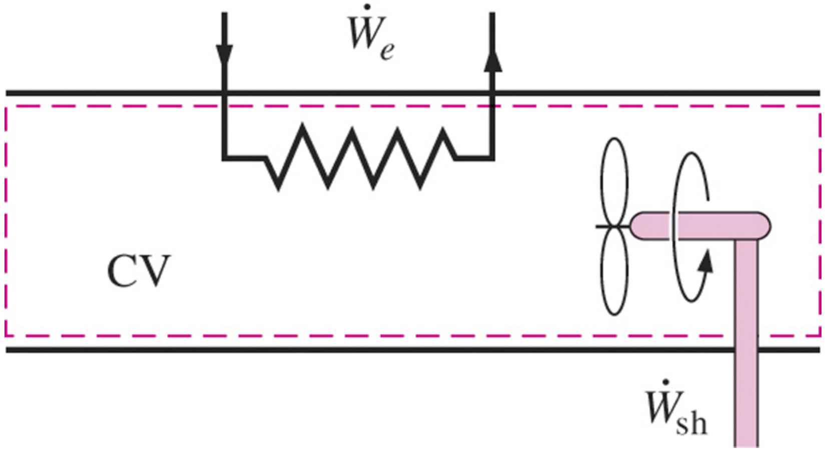
$$q - w = h_2 - h_1 \quad q = \dot{Q}/\dot{m} \quad w = \dot{W}/\dot{m}$$

when kinetic and potential energy changes are negligible

$$\frac{\text{J}}{\text{kg}} \equiv \frac{\text{N}\cdot\text{m}}{\text{kg}} \equiv \left(\text{kg}\frac{\text{m}}{\text{s}^2}\right)\frac{\text{m}}{\text{kg}} \equiv \frac{\text{m}^2}{\text{s}^2}$$

$$\left(\text{Also, } \frac{\text{Btu}}{\text{lbm}} \equiv 25{,}037\ \frac{\text{ft}^2}{\text{s}^2}\right)$$

Some energy unit equivalents



Under steady operation, shaft work and electrical work are the only forms of work a simple compressible system may involve.

Next lecture

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