EPFL

ETA-Lab
Energy Transport Advances

ME-251: Thermodynamics and energetics I
First Law for Open Systems

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Last Time

- Estimate thermodynamic properties in special cases
  - Incompressible substance
  - Ideal gas

○ Reading: Moran 3.10-3.15

Brain Teaser

- Which of the following statements describes a supercritical fluid?
  - A. A substance at a temperature and pressure **both** below its critical point, exhibiting distinct liquid and gas phases.
  - B. A substance at a temperature above its critical point temperature **or** at a pressure above its critical pressure, where liquid and gas phases are indistinguishable.
  - C. substance at a temperature and pressure **both** above its critical point, where liquid and gas phases are indistinguishable.
  - D. A substance at its triple point, where solid, liquid, and gas phases coexist in equilibrium.

Scan the QR code with your device
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Enter Code

luepfl

Additional rationale on du = c_v dT for ideal gas expansion or compression

- For ideal gas, *u* is only a function of temperature

- For any process between state 1 and state 2 with varying specific volume $v_1 \neq v_2$, consider a process that brings state 1 to state 2', in which $v_1 = v_{2'}$ and $T_2 = T_{2'}$

- Note that for ideal gas, $u_2 = u_{2'}$ and $u_2 - u_1 = u_{2'} - u_1$

- The internal energy change does not depend on whether the volume is held constant

Incompressible Substance

- Liquids and solids are often modeled as incompressible v = const

$$u = u(T) \qquad c_v = \frac{du}{dT} = c(T) = c_p \qquad \text{At constant } T, dh = v dp$$

Ideal Gas

- $\frac{pv}{RT} = \frac{p\tilde{v}}{\tilde{R}T} = Z \equiv 1$, the dilute limit of real gases

T: temperature [K]
$\tilde{R}$: universal gas constant [J/K/mol]
R: specific gas constant [J/K/kg]
$\tilde{v}$: molar volume [m^3/mol]

$u = u(T)$ $\quad$ $h = u + pv = u(T) + RT$ $\quad$ $c_v = \frac{du}{dT} = c(T)$ $\quad$ $c_p = c_v(T) + R$

Specific heat ratio $k = \frac{c_p}{c_v} = 1 + \frac{R}{c_v}$

Additional rationale on du = c_v dT for ideal gas expansion or compression

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Perfect Gas

Follows ideal gas law

$$c_v = \text{const}, \qquad c_p = c_v + R$$

Common approximations:

Monoatomic $c_v = 1.5R$

Diatomic $c_v = 2.5\ R$

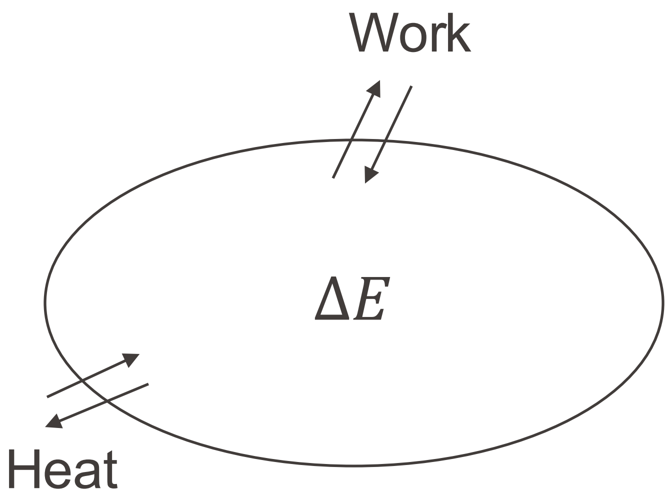
Polyatomic: $c_v = 3R$

ILOs Today

- Understand the difference between the analyses of closed and open systems
- Apply mass balance to open systems
- Apply energy balance to open systems

- Reading: Moran 4.1 - 4.5

First Law of Thermodynamics (Intuition)



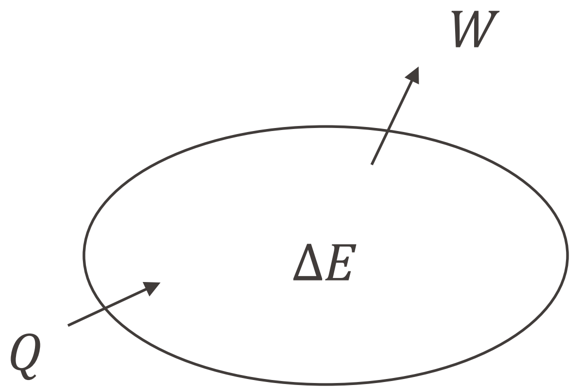
Can be intuitively understood as energy conservation

Energy change = Energy going in – Energy going out

Energy flows can take the form of heat, work, …

First Law of Thermodynamics for Closed Systems

Change in the amount of energy contained within a system during some time interval	=	Net amount of energy transferred **into** the system by heat transfer during the time interval	−	Net amount of energy transferred **out of** the system by work during the time interval

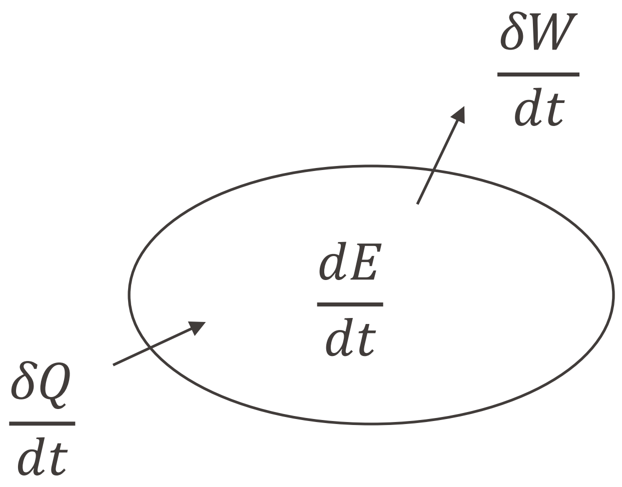


$$\Delta E = E_2 - E_1 = Q - W$$

Everything is in [J]

Time Rate Form of First Law for Closed Systems

Time rate of change in the amount of energy contained within a system at time *t*	=	Net rate at which energy is transferred **into** the system by heat transfer at time *t*	−	Net rate at which energy is transferred **out of** the system by work at time *t*



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

Heat flow rate - Power

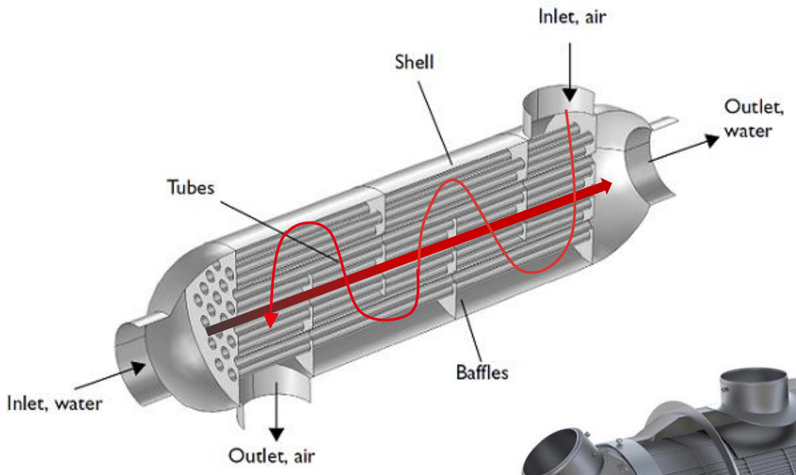
Everything is in [W]

Components in First Law

- Type of work transfer
  - Expansion/compression (e.g., polytropic processes)
  - Electrical, spring, shaft,…
- Type of energy
  - Potential energy
  - Kinetic energy
  - Internal energy (thermal motion, latent, chemical, nuclear,…)
- Type of heat transfer (requires temperature gradient)
  - Conduction, convection, radiation

Real World Open Systems

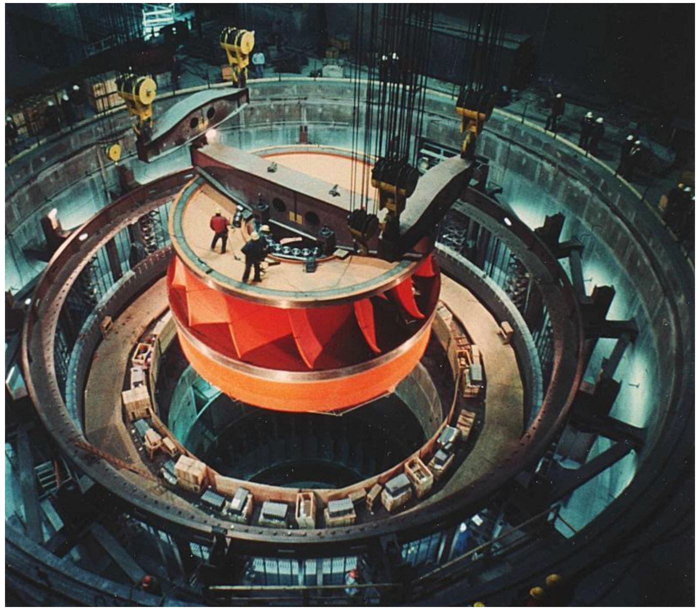
- Open systems: systems with mass transport across the boundary
  - Heat exchangers



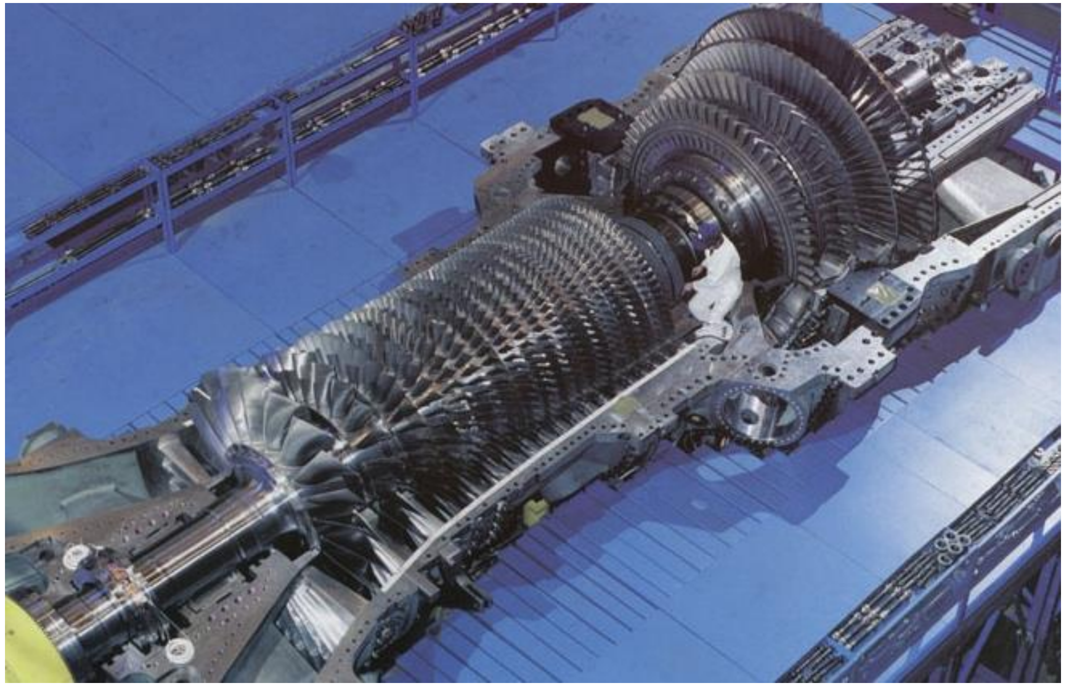
Alstom, Feedwater heater for nuclear power plant, 500 MW

Real World Open Systems

- E.g., turbines



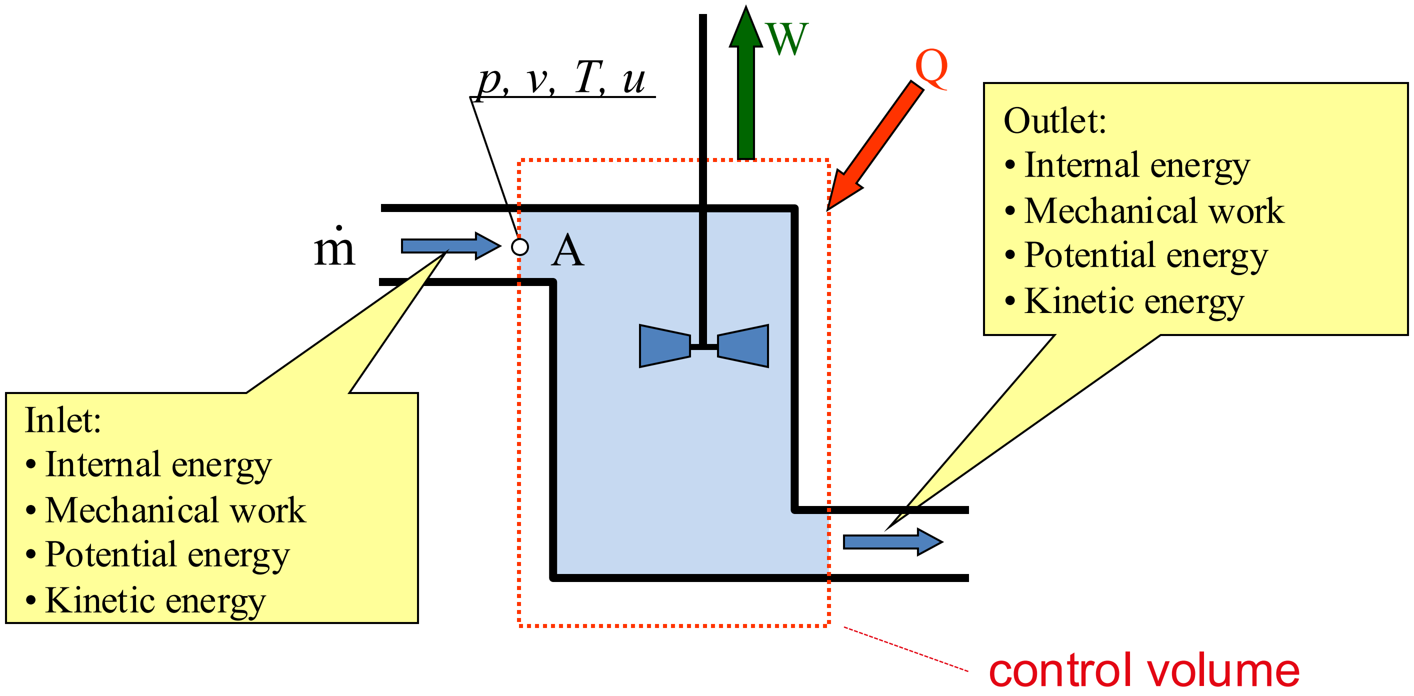
Francis turbine, Grand Coulee Dam,
biggest hydro plant in the US,
capacity 6800 MW, 33 turbines (different sizes)



GE 9H gas turbine, 480 MW

Many real-world systems deal with flowing working fluid: turbines, engines, compressors, heat exchangers,…

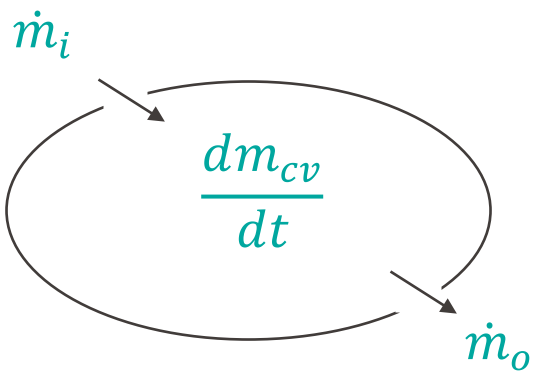
First Law for Open Systems



Unlike closed systems, energy transfer can be due to incoming and outgoing mass flow

With opens systems, we consider both mass conservation and energy conservation

Mass Conservation

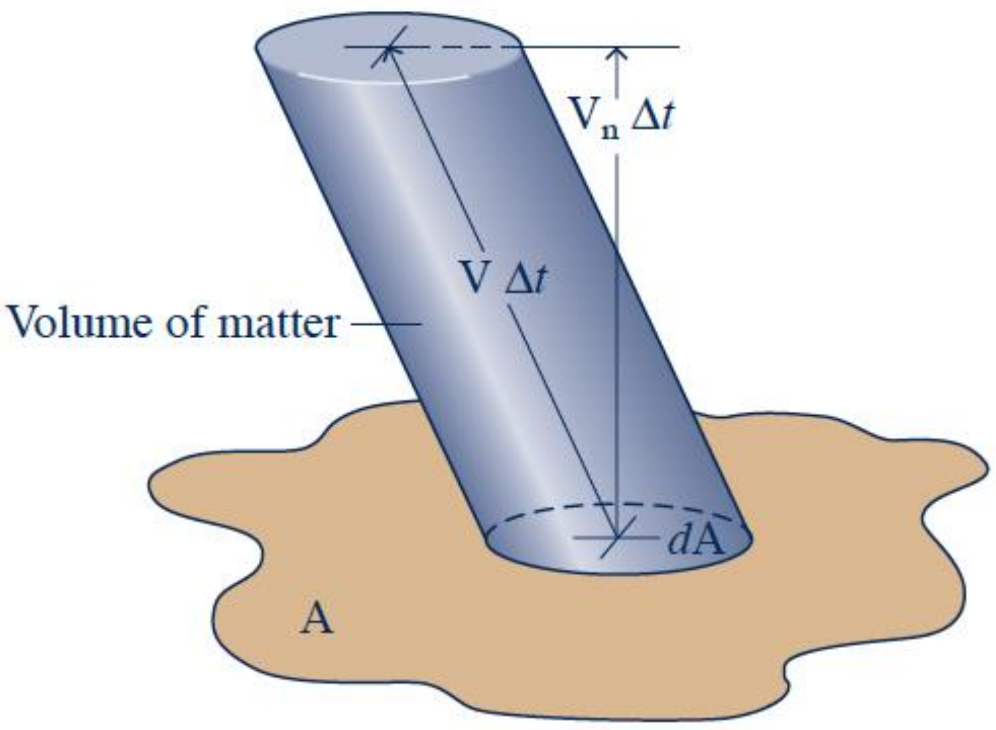


$$\frac{dm_{cv}}{dt} = \sum_i \dot{m}_i - \sum_o \dot{m}_o \qquad \text{[kg/s]}$$

In general, there could be several inlets and outlets

Time rate of change in the amount of mass contained within a control volume at time *t*	=	Rate at which mass is transferred **into** the system at time *t*	–	Rate at which mass is transferred **out of** the system at time *t*

How to Evaluate Mass Flow Rates



In Moran, non-italic V represents velocity

- Consider a small quantity of matter flowing with velocity V across an incremental area dA in a small time interval Δt

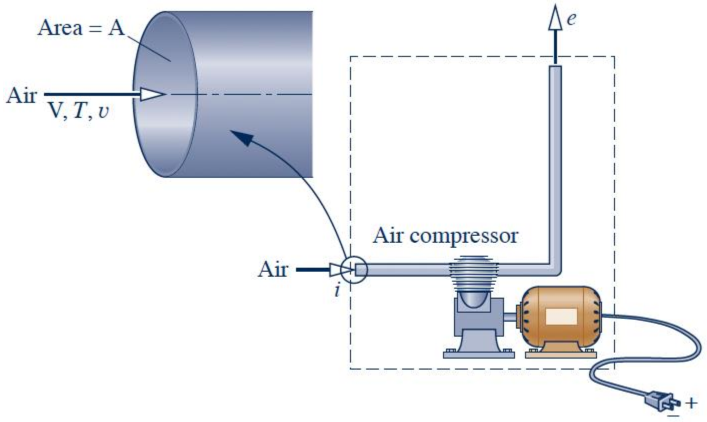
$$\begin{bmatrix}\text{amount of mass} \\ \text{crossing } dA \text{ during} \\ \text{time interval } \Delta t\end{bmatrix} = \rho(\mathrm{V}_n \Delta t)\, dA$$

$$\begin{bmatrix}\text{instantaneous rate} \\ \text{of mass flow} \\ \text{across } dA\end{bmatrix} = \rho \mathrm{V}_n\, dA$$

$$\dot{m} = \int_A \rho \mathrm{V}_n\, dA$$

Special Cases

- 1D form of the mass rate balance
  - The flow is normal to the boundary at locations where mass enters or exits the control volume ($V = V_n$)
  - Velocity and density are uniform over the specified inlet or exit area



$$\dot{m} = \rho A V$$

$$\frac{dm_{cv}}{dt} = \sum_i \rho_i A_i V_i - \sum_o \rho_o A_o V_o$$

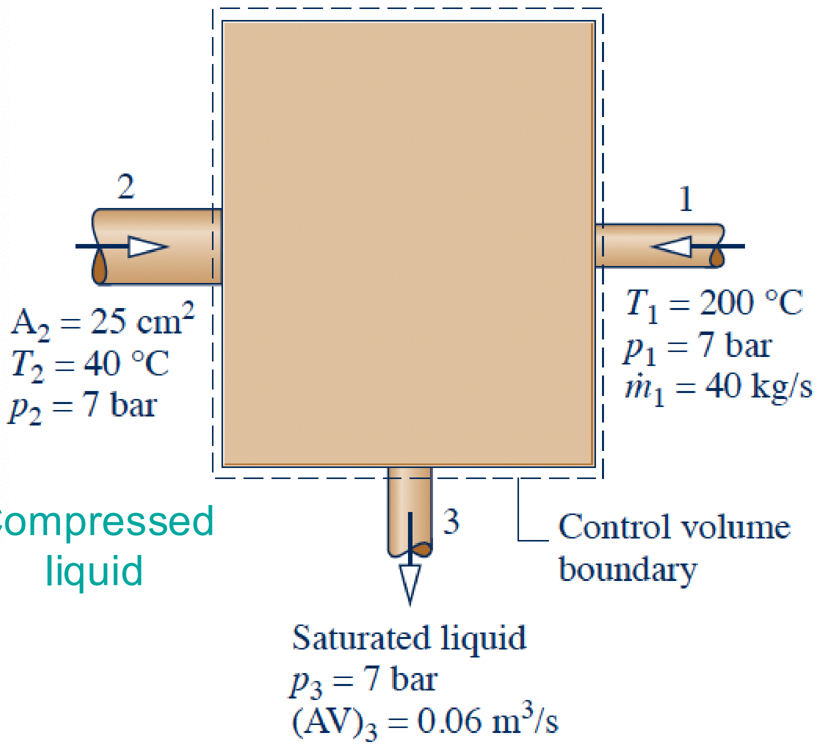
Special Cases

- Steady state: all properties in the control volume are invariant over time

$$\sum_i \dot{m}_i = \sum_o \dot{m}_o$$

- Steady mass in a control volume does not necessarily mean that the system is at a steady state (other properties can change)

Example 4.1 in Moran



Compressed liquid

A feedwater heater operating at steady state

Determine the mass flow rates at inlet 2 and at the exit, and the velocity V_2

$v_3 = 1.108 \times 10^{-3}$ m³/kg

Approximate liquid water as incompressible substance

$$\frac{dm_{cv}}{dt} = \dot{m}_1 + \dot{m}_2 - \dot{m}_3$$

$$\dot{m}_2 = \dot{m}_1 - \dot{m}_3$$

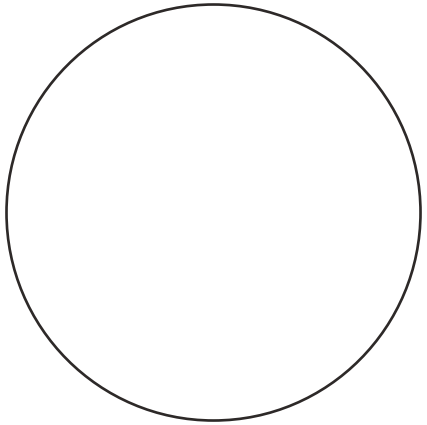
$$\dot{m}_3 = \frac{(AV)_3}{v_3}$$

$$V_2 = \dot{m}_2 v_2 / A_2$$

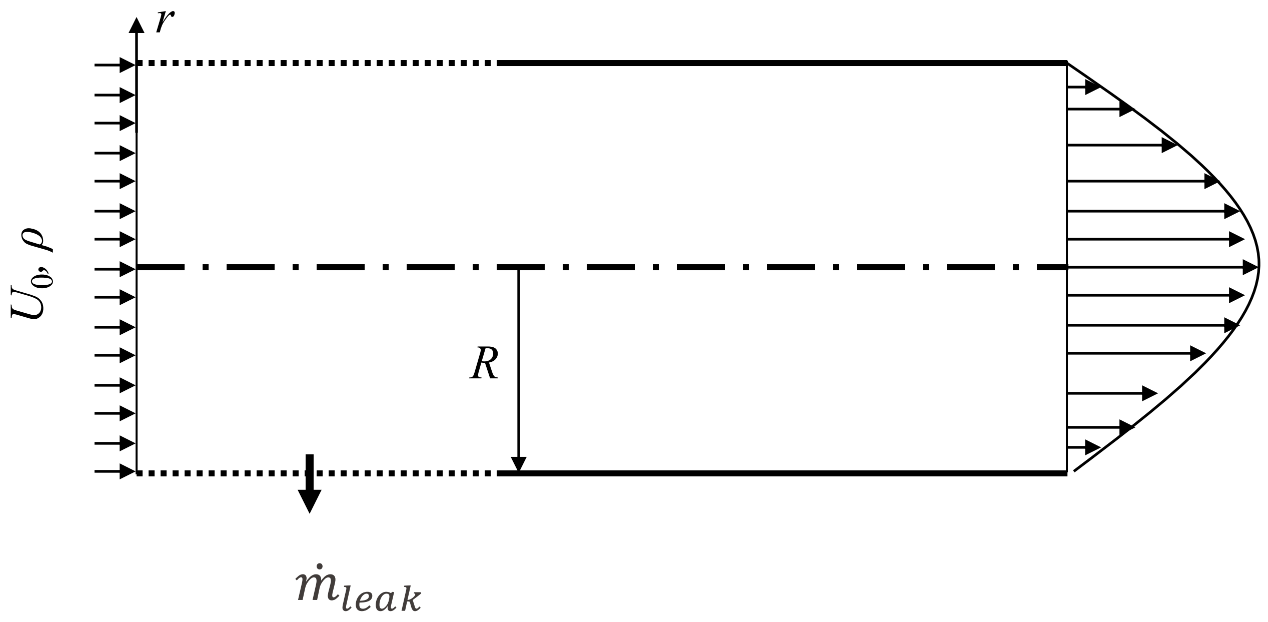
$$v_2 = v_3$$

Integral Form

Example: steady-state pipe flow with steady leakage
(inlet and outlet velocities normal to the surface)



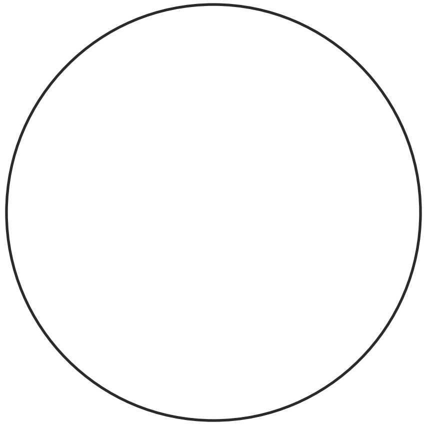
Cross-section

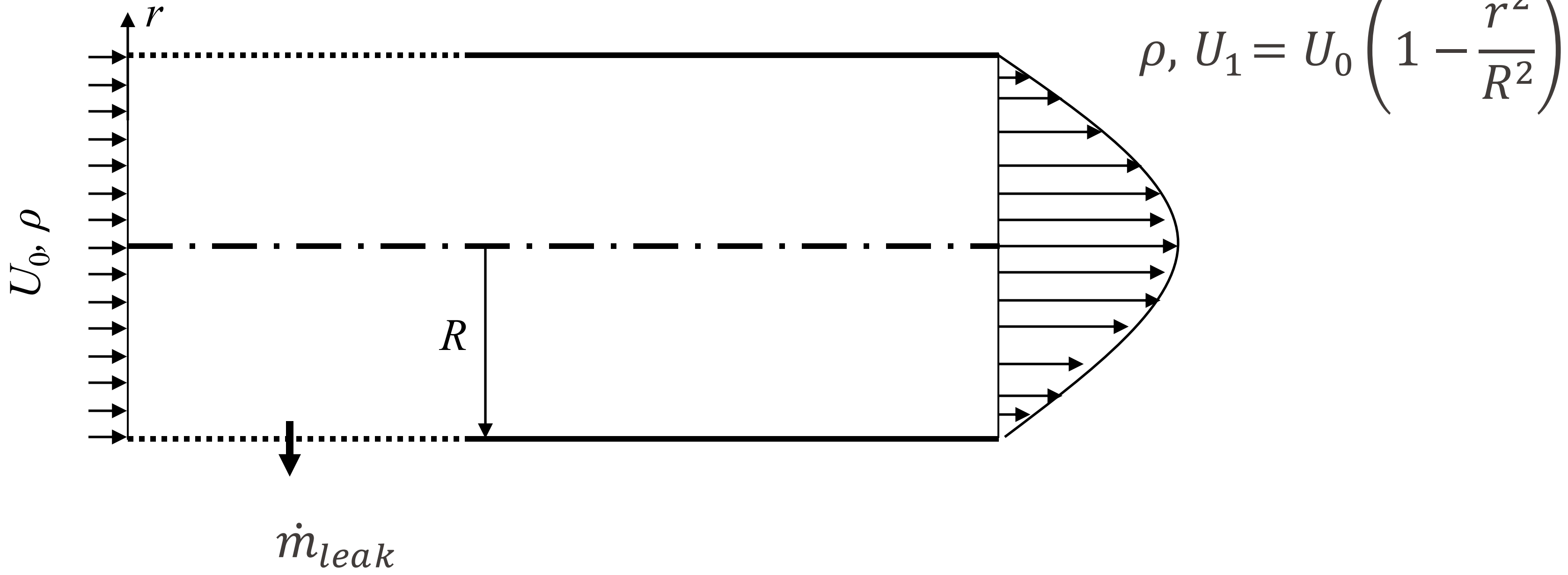


$$\rho,\ U_1 = U_0\left(1 - \frac{r^2}{R^2}\right)$$

Calculate the mass flow rate leaking through the perforated pipe wall

Integral Form

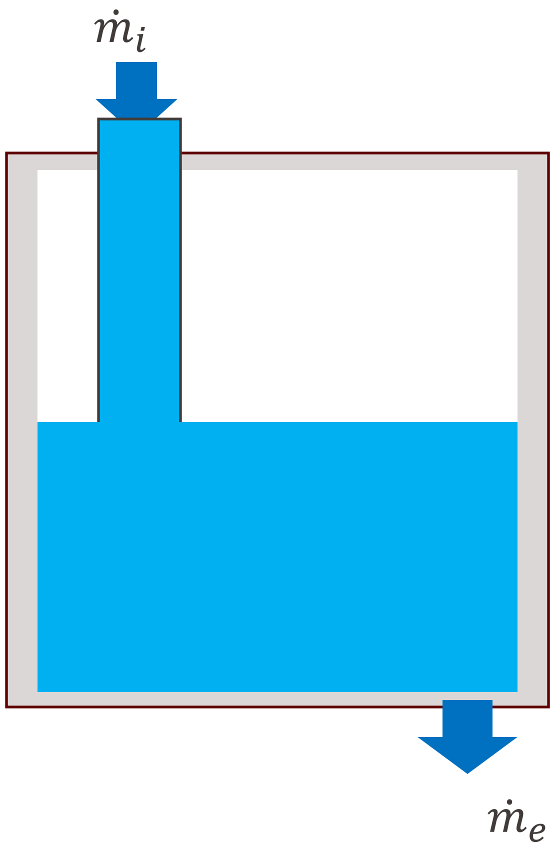




$$\rho U_0 \pi R^2 = \dot{m}_{leak} + \int_0^R \rho U_1 2\pi r dr$$

$$\dot{m}_{leak} = \rho U_0 \pi R^2 - \int_0^R \rho U_1 2\pi r dr = \rho U_0 \pi R^2 - \frac{1}{2}\rho U_0 \pi R^2 = \frac{\pi}{2}\rho U_0 R^2$$

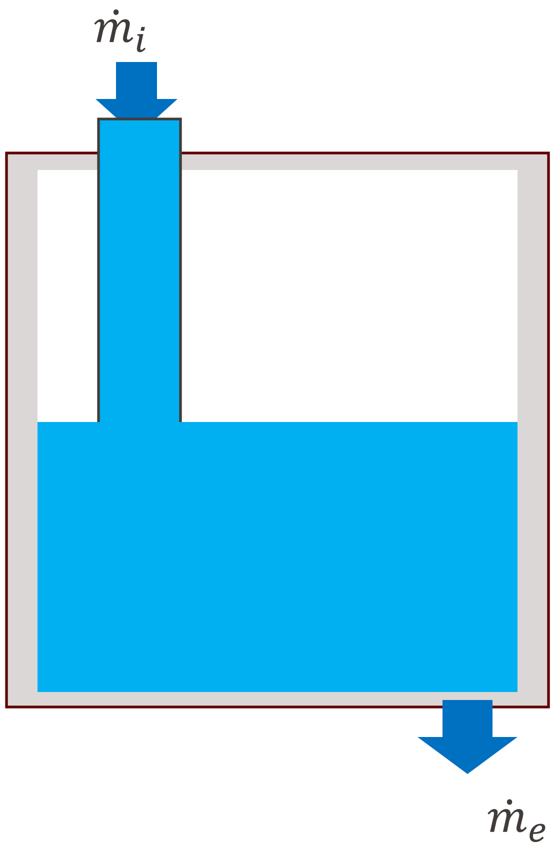
Example 4.2 in Moran (Transient Mass Balance)



- Water enters and exits an initially empty barrel.
  - Inlet flow rate is $\dot{m}_i = 7$ kg/s
  - Outlet flow rate is proportional to the height of liquid inside $\dot{m}_e = 1.4L$, where L is the instantaneous liquid height (SI units)
  - Base area of the barrel is $A = 0.2\ \text{m}^2$ and density of water is $\rho = 1000\ \text{kg/m}^3$

Plot the variation of liquid height *L* as a function of time *t*

Example 4.2 in Moran (Transient Mass Balance)



$$\frac{dm_{cv}}{dt} = \dot{m}_i - \dot{m}_e$$

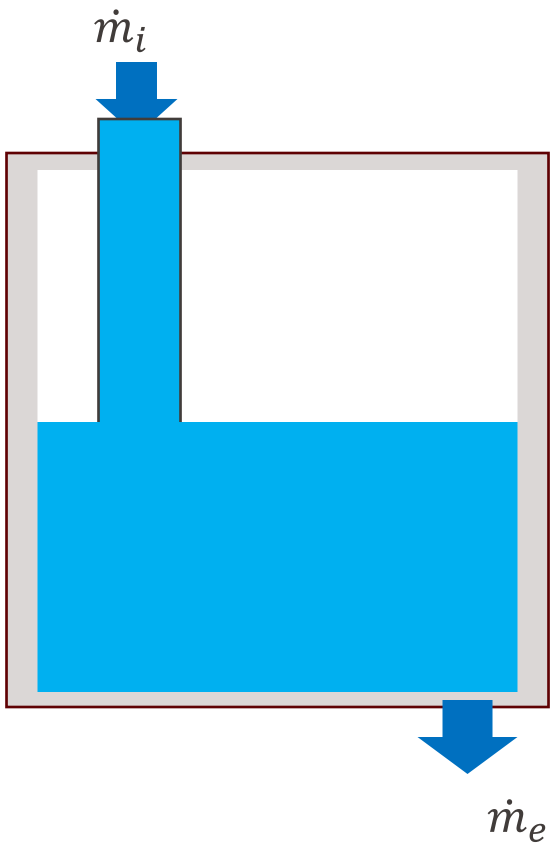
$$\frac{d(\rho A L)}{dt} = 7 - 1.4L \qquad \text{SI units } \rho A = 200 \text{ [kg/m]}$$

$$\frac{dL}{dt} + 0.007(L - 5) = 0$$

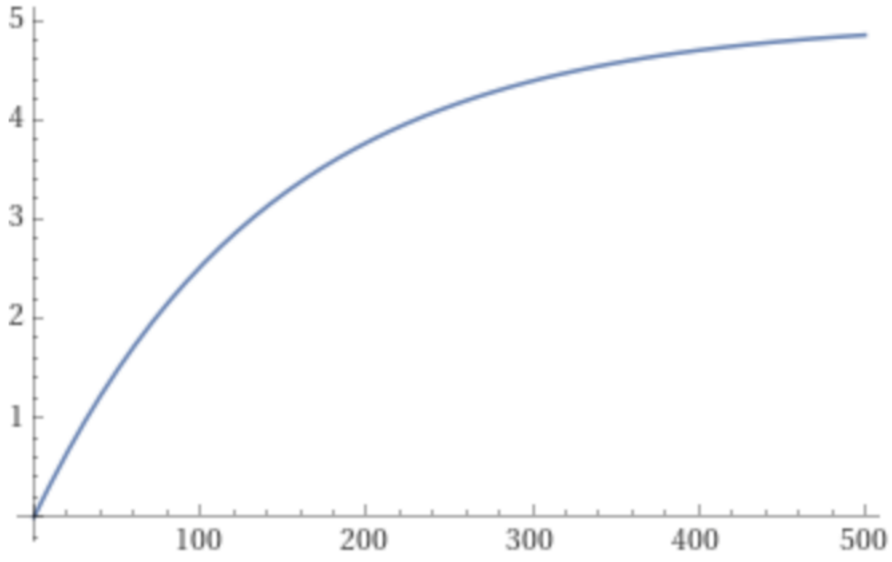
$$L = 5 + C\exp(-0.007t)$$

$t = 0$, $L = 0$ $\Rightarrow C = -5$ $\qquad L = 5[1 - \exp(-0.007t)]$

Example 4.2 in Moran (Transient Mass Balance)

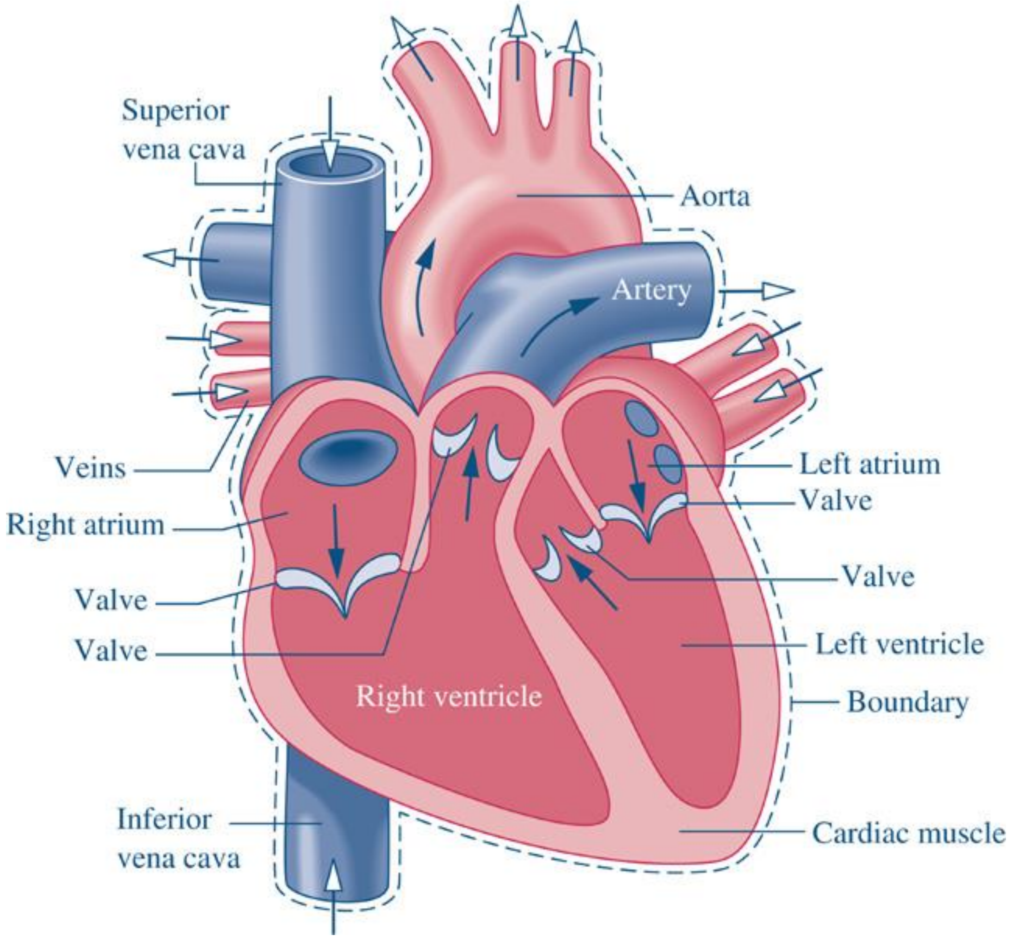


$$L = 5[1 - \exp(-0.007t)]$$



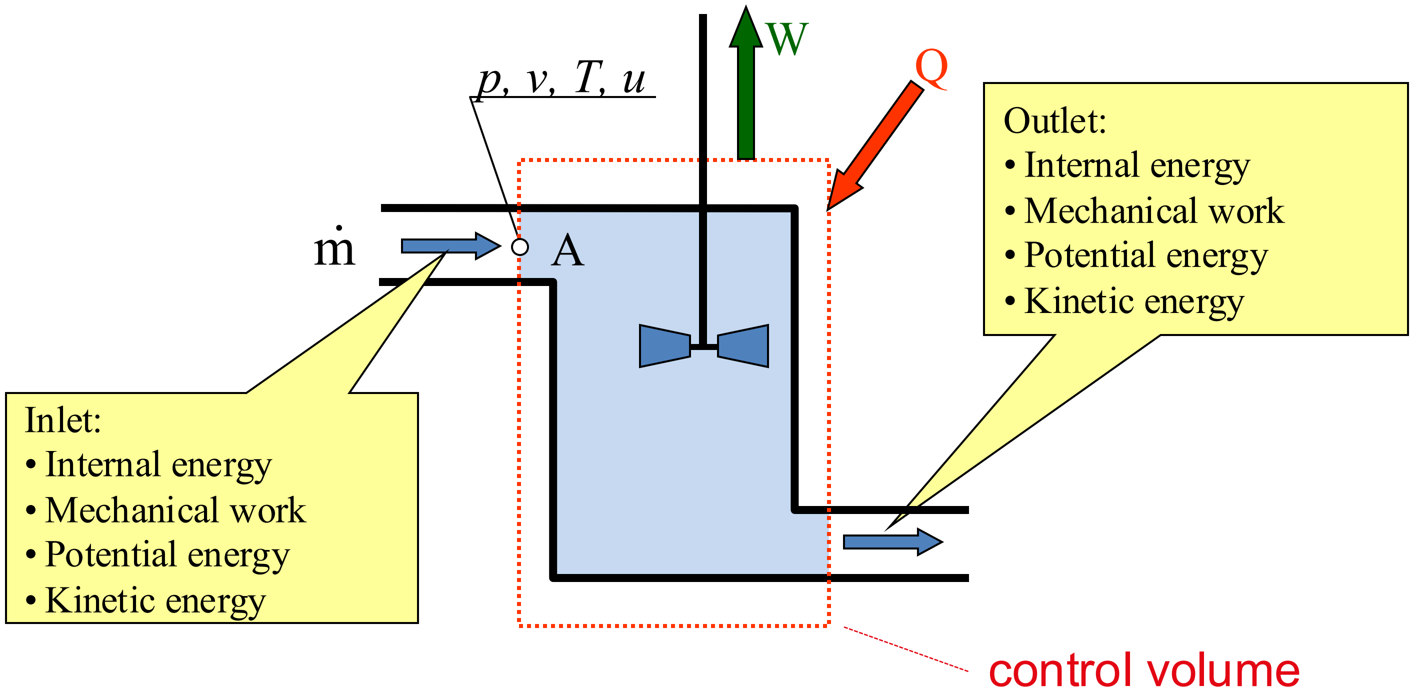
Filling height saturated around 5 m

Bio-Connection



- Flow in a human heart is controlled by valves that intermittently allow blood to enter and exit as the heart muscles pump
- The boundary of this control volume is moving as the heart pulses

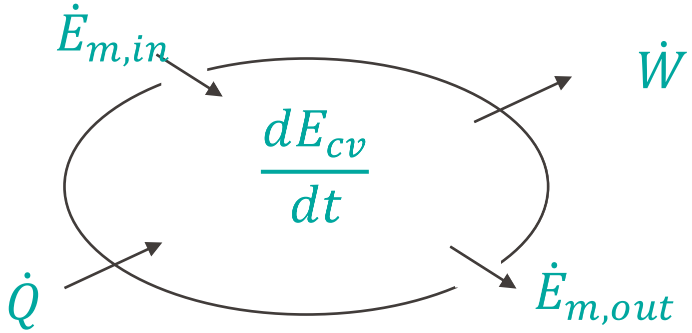
First Law for Open Systems



Unlike closed systems, energy transfer can be due to incoming and outgoing mass flow

First Law for Open Systems

- Energy rate balance

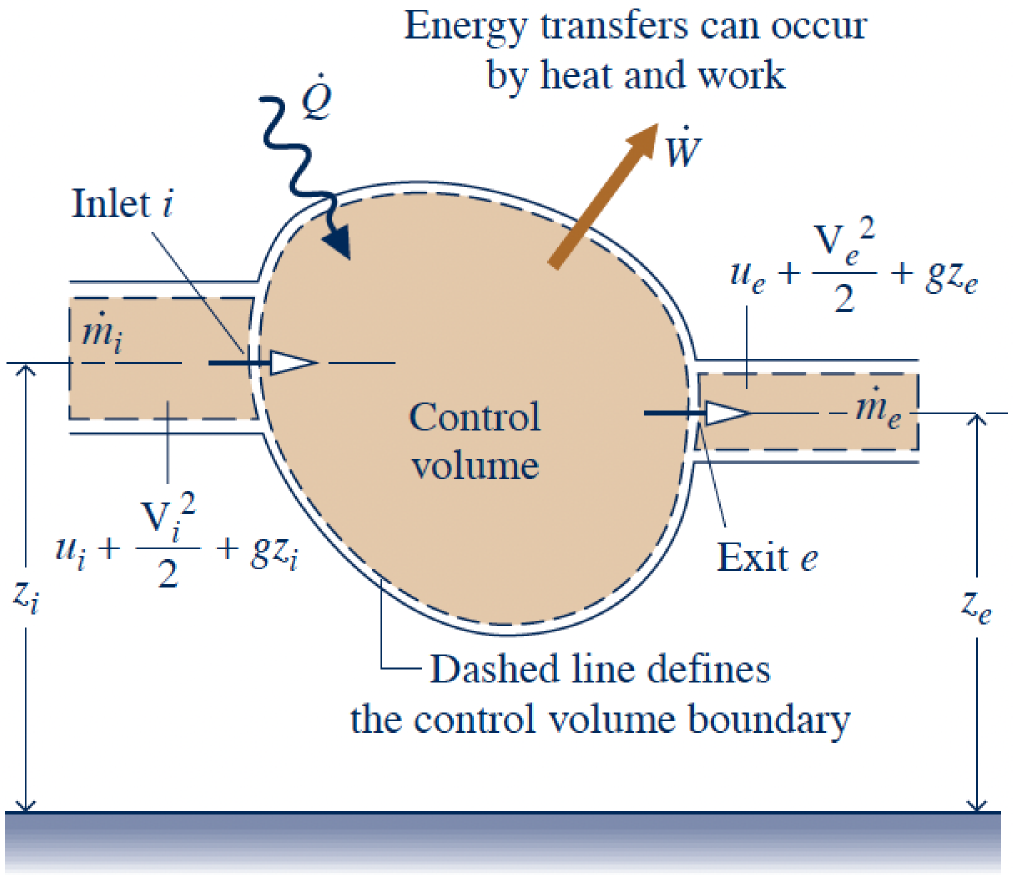


Time rate of change in the amount of energy contained within a control volume at time *t*

=

Net rate at which energy is transferred into the system by heat transfer at time *t*	−	Net rate at which energy is transferred out of the system by work at time *t*	+	Net rate at which energy is transferred into the system by accompanying **mass flow**

One-Inlet One-Exit Control Volume

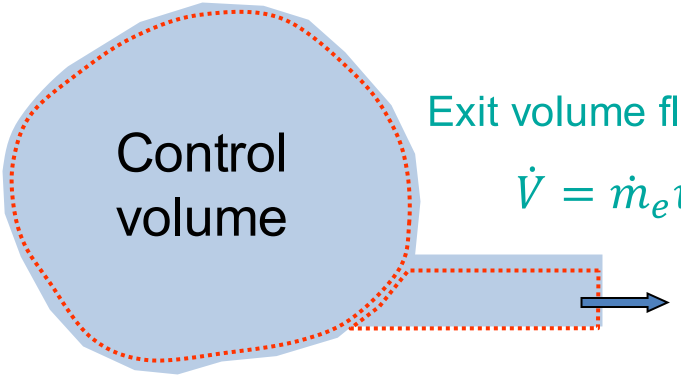


$$\frac{dE_{cv}}{dt} = \dot{Q} - \dot{W}$$
$$+\dot{m}_i\left(u_i + \frac{V_i^2}{2} + gz_i\right)$$
$$-\dot{m}_e\left(u_e + \frac{V_e^2}{2} + gz_e\right)$$

Flow Work on Control Volume

- Separate $\dot{W}$ into two contributions
  - Work associated with fluid pressure as mass is introduced at inlets and removed at exits (rate of flow work)
  - All other works $\dot{W}_{cv}$

Rate of energy transfer by work **out of** control volume at exit	$= p_e\dot{V} = p_e\dot{m}_e v_e$
Rate of energy transfer by work **into** control volume at inlet	$= \dot{m}_i(p_i v_i)$



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

Energy Balance Rewritten

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

One-inlet, one-outlet

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

Recall enthalpy is defined as $h = u + pv$

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

More than one inlet and one outlet

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

Integral Form

$$E_{CV} = \int_{\mathcal{V}} \rho \left(u + \frac{\vec{V}^2}{2} + gz \right) d\mathcal{V}$$

$$\frac{d}{dt} \int_{\mathcal{V}} \rho \left(u + \frac{\vec{V}^2}{2} + gz \right) d\mathcal{V} = \dot{Q}_{cv} - \dot{W}_{cv} + \sum_i \left[\int_A \left(h + \frac{\vec{V}^2}{2} + gz \right) \rho \vec{V} \cdot d\vec{A} \right]_i - \sum_e \left[\int_A \left(h + \frac{\vec{V}^2}{2} + gz \right) \rho \vec{V} \cdot d\vec{A} \right]_e$$

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

Mass + Energy Conservation for CV

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

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

At steady state this reduces to

$$0 = \sum_i \dot{m}_i - \sum_o \dot{m}_o$$

$$0 = \dot{Q}_{cv} - \dot{W}_{cv} + \sum_i \dot{m}_i \left(h_i + \frac{\vec{V}_i^2}{2} + gz_i \right) - \sum_e \dot{m}_e \left(h_e + \frac{\vec{V}_e^2}{2} + gz_e \right)$$