Thermodynamics
ENGR360-MEP112

LECTURE 7

Objectives:

1. **Conservation of mass principle.**
2. **Conservation of energy principle applied to control volumes (first law of thermodynamics).**
3. **Energy balance of common steady-flow devices such as nozzles, diffusers, compressors, turbines, throttling valves, mixing chambers and heat exchangers.**

1. CONSERVATION OF MASS

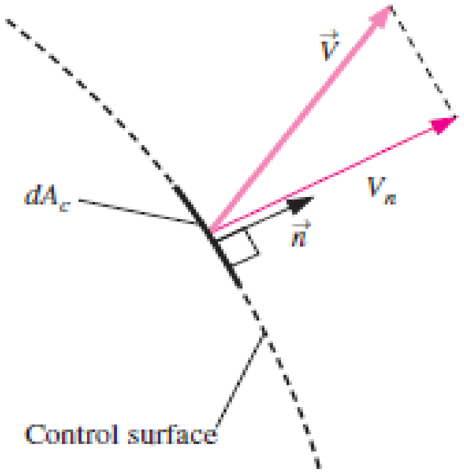
❑ Mass and Volume Flow Rates:

$$\text{Mass flow rate, } \dot{m} = \int_{A_c} \rho v_n dA_c$$

$$\boxed{\dot{m} = \rho v_n A_c}$$

$$\text{Volume flow rate, } \dot{V} = \frac{\dot{m}}{\rho} = \int_{A_c} v_n dA_c$$

$$\boxed{\dot{V} = v_n A_c}$$



The normal velocity V_n for a surface is the component of velocity perpendicular to the surface.

$\hat{n}$: normal unit vector

$\vec{V}$: Flow velocity

$\overrightarrow{V_n}$: normal flow velocity

A_c: cross – sectional area of flow

1. CONSERVATION OF MASS

❑ Conservation of Mass Principle:

The conservation of mass principle for a control volume can be expressed as: ***The net mass transfer to or from a control volume during a time interval Δt is equal to the net change (increase or decrease) in the total mass within the control volume during Δt. That is,***

$$\left(\begin{matrix}\text{Total mass}\\ \text{entering the CV during }\Delta t\end{matrix}\right)-\left(\begin{matrix}\text{Total mass}\\ \text{leaving the CV during }\Delta t\end{matrix}\right)=\left(\begin{matrix}\text{Net change in}\\ \text{mass within CV during }\Delta t\end{matrix}\right)$$

$$\boxed{\sum m_{in}\Big|_{CS}-\sum m_{out}\Big|_{CS}=\Delta m_{CV}}$$

In a rate form:

$$\boxed{\sum \dot{m}_{in}\Big|_{CS}-\sum \dot{m}_{out}\Big|_{CS}=\frac{dm_{CV}}{dt}}$$

1. CONSERVATION OF MASS

$$\frac{dm_{CV}}{dt} = \frac{d(\rho V_{CV})}{dt} = \frac{d}{dt}\int_{CV}(\rho dV + V d\rho)$$

- ○ The rate of change of the mass within the control volume (CV) is due to the change of its volume dV and the change of the density of the fluid $d\rho$.

- ○ $\frac{dm_{CV}}{dt} = 0$ if there is no change in volume dV and no change in density $d\rho$.

1. CONSERVATION OF MASS

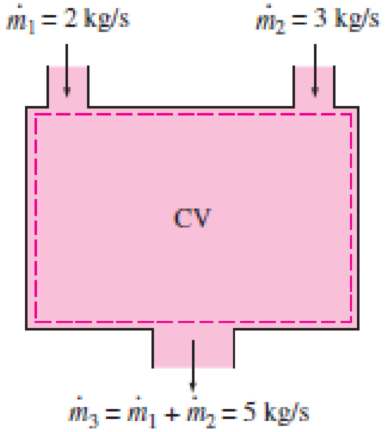
☐ Mass Balance for Steady-Flow Processes:

During a steady-flow process, the total amount of mass contained within a control volume does not change with time (m_{CV} = constant).

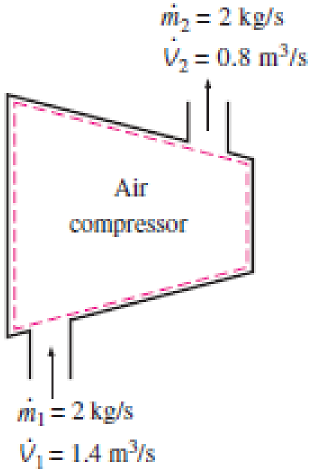
$$\sum \dot{m}_{in}\Big|_{CS} = \sum \dot{m}_{out}\Big|_{CS}$$

○ **For steady-incompressible flow, i.e ρ = constant:**

$$\sum \dot{V}_{in}\Big|_{CS} = \sum \dot{V}_{out}\Big|_{CS}$$



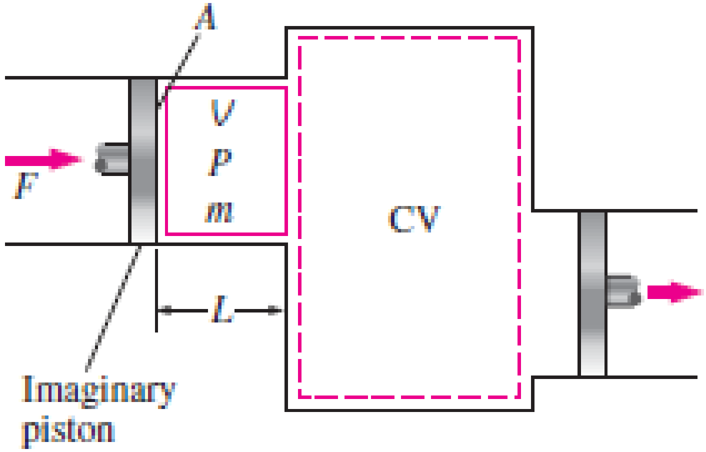
Conservation of mass principle for a two-inlet–one-outlet steady-flow system.



During a steady-flow process, volume flow rates are not necessarily conserved although mass flow rates are.

2. FLOW WORK AND THE ENERGY OF A FLOWING FLUID

- ☐ **Unlike closed systems, control volumes involve mass flow across their boundaries, and some work is required to push the mass into or out of the control volume. This work is known as the *flow work*, or *flow energy*, and is necessary to maintain a continuous flow through a control volume.**



Schematic for flow work.

$$\mathbf{W_{flow} = F.L = p.A.L = pV\ (J)}$$

$$\mathbf{w_{flow} = p}v\ \mathbf{(J/kg)}$$

2. FLOW WORK AND THE ENERGY OF A FLOWING FLUID

☐ **For closed system:**

$$\mathbf{e = u + ke + pe}$$

☐ **For open system (control volume):**

The energy contained in a flowing fluid is θ

$$\boldsymbol{\theta} = \mathbf{e} + \underbrace{\mathbf{p}v}_{\text{flow work}} = \mathbf{p}v + \mathbf{u + ke + pe}$$

$$\boldsymbol{\theta} = \mathbf{h + ke + pe}$$

☐ **Energy Transport by Mass:**

○ **Amount of energy transport:** $\mathbf{E_{mass}} = \mathbf{m}\boldsymbol{\theta} = \mathbf{m(h + ke + pe)}$

○ **Rate of energy transport:** $\dot{\mathbf{E}}_{\mathbf{mass}} = \dot{\mathbf{m}}\boldsymbol{\theta} = \dot{\mathbf{m}}\mathbf{(h + ke + pe)}$

3. ENERGY ANALYSIS OF STEADY-FLOW SYSTEMS

- **First law of thermodynamics for open-steady flow systems:**

$$\boxed{\dot{E}_{in} - \dot{E}_{out} = \cancel{\frac{dE_{system}}{dt}}}$$

Zero, for steady-state steady-flow process

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{Q}_{in} + \dot{W}_{in} + \dot{E}_{mass,in} = \dot{Q}_{out} + \dot{W}_{out} + \dot{E}_{mass,out}$$

$$\dot{Q}_{in} + \dot{W}_{in} + \sum_{in}^{CS} \dot{m}\theta = \dot{Q}_{out} + \dot{W}_{out} + \sum_{out}^{CS} \dot{m}\theta$$

$$\boxed{\dot{Q}_{in} + \dot{W}_{in} + \sum_{in}^{CS} \dot{m}\left(h + \frac{v^2}{2} + gz\right) = \dot{Q}_{out} + \dot{W}_{out} + \sum_{out}^{CS} \dot{m}\left(h + \frac{v^2}{2} + gz\right)}$$

3. ENERGY ANALYSIS OF STEADY-FLOW SYSTEMS

❑ Special cases:

1. **Single stream ($\dot{m}_{in} = \dot{m}_{out} = \dot{m}$:**

$$\dot{Q}_{in} + \dot{W}_{in} + \dot{m}\left(h_{in} + \frac{v_{in}^2}{2} + gz_{in}\right) = \dot{Q}_{out} + \dot{W}_{out} + \dot{m}\left(h_{out} + \frac{v_{out}^2}{2} + gz_{out}\right)$$

2. **Single stream per unit $\dot{m}$ (single stream per unit mass per unit time):**

$$q_{in} + w_{in} + h_{in} + \frac{v_{in}^2}{2} + gz_{in} = q_{out} + w_{out} + h_{out} + \frac{v_{out}^2}{2} + gz_{out}$$

3. **Single stream per unit $\dot{m}$ with negligible kinetic and potential energies:**

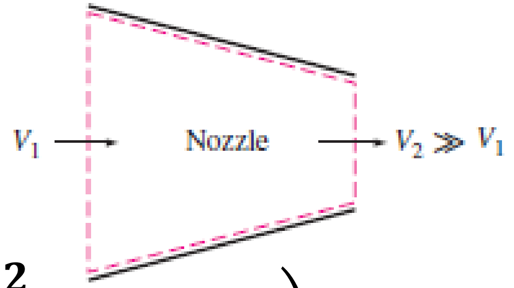
$$q_{in} + w_{in} + h_{in} = q_{out} + w_{out} + h_{out}$$

or

$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = h_{out} - h_{in}$$

4. SOME STEADY-FLOW ENGINEERING DEVICES

➢ Nozzle:



- ***Nozzle*** **is a device that increases the velocity of a fluid at the expense of its pressure.**
- ***Nozzle*** **can be used with compressible or incompressible fluid flow.**
- **Energy balance for single stream:**

$$\dot{Q}_{in} + \underset{\text{Zero}}{\cancel{\dot{W}_{in}}} + \dot{m}_{in}\left(h_{in} + \frac{v_{in}^2}{2} + gz_{in}\right) = \dot{Q}_{out} + \underset{\text{Zero}}{\cancel{\dot{W}_{out}}} + \dot{m}_{out}\left(h_{out} + \frac{v_{out}^2}{2} + gz_{out}\right)$$

$$\left(\dot{Q}_{in} - \dot{Q}_{out}\right) = \dot{m}\left[(h_2 - h_1) + \left(\frac{v_2^2 - v_1^2}{2}\right) + g(z_2 - z_1)\right]$$

For single stream and neglected change in potential energy:

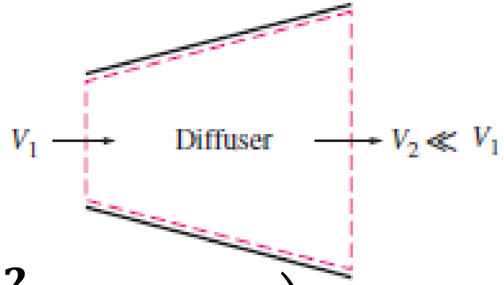
$$\left(\dot{Q}_{in} - \dot{Q}_{out}\right) = \dot{m}\left[(h_2 - h_1) + \left(\frac{v_2^2 - v_1^2}{2}\right)\right]$$

For single stream, neglected change in potential energy and adiabatic nozzle:

$$(h_2 - h_1) = \left(\frac{v_1^2 - v_2^2}{2}\right)$$

4. SOME STEADY-FLOW ENGINEERING DEVICES

➢ Diffuser:



- ***Diffuser*** is a device that increases the pressure of a fluid by slowing it down.
- ***Diffuser*** can be used with compressible or incompressible fluid flow.
- **Energy balance for single stream:**

$$\dot{Q}_{in} + \underset{\text{Zero}}{\dot{W}_{in}} + \dot{m}_{in}\left(h_{in} + \frac{v_{in}^2}{2} + gz_{in}\right) = \dot{Q}_{out} + \underset{\text{Zero}}{\dot{W}_{out}} + \dot{m}_{out}\left(h_{out} + \frac{v_{out}^2}{2} + gz_{out}\right)$$

$$\left(\dot{Q}_{in} - \dot{Q}_{out}\right) = \dot{m}\left[(h_2 - h_1) + \left(\frac{v_2^2 - v_1^2}{2}\right) + g(z_2 - z_1)\right]$$

For single stream and neglected change in potential energy:

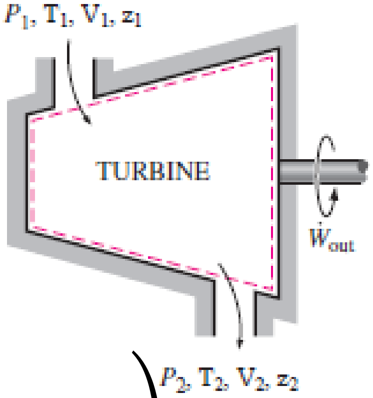
$$\left(\dot{Q}_{in} - \dot{Q}_{out}\right) = \dot{m}\left[(h_2 - h_1) + \left(\frac{v_2^2 - v_1^2}{2}\right)\right]$$

For single stream, neglected change in potential energy and adiabatic diffuser:

$$(h_2 - h_1) = \left(\frac{v_1^2 - v_2^2}{2}\right)$$

4. SOME STEADY-FLOW ENGINEERING DEVICES

➢ Turbine:



- ***Turbine*** **is a device that produces power from the fluid.**
- ***Gas turbine, steam turbine and wind turbine*** **use a compressible fluid flow.**
- ***Water turbine*** **uses an incompressible fluid flow.**
- **Energy balance for single stream fluid flow:**

$$\dot{Q}_{in} + \underbrace{\cancel{\dot{W}_{in}}}_{\text{Zero}} + \dot{m}_{in}\left(h_{in} + \frac{v_{in}^2}{2} + gz_{in}\right) = \dot{Q}_{out} + \dot{W}_{out} + \dot{m}_{out}\left(h_{out} + \frac{v_{out}^2}{2} + gz_{out}\right)$$

$$\left(\dot{Q}_{in} - \dot{Q}_{out}\right) - \dot{W}_{out} = \dot{m}\left[(h_2 - h_1) + \left(\frac{v_2^2 - v_1^2}{2}\right) + g(z_2 - z_1)\right]$$

For single stream and neglected change in potential energy:

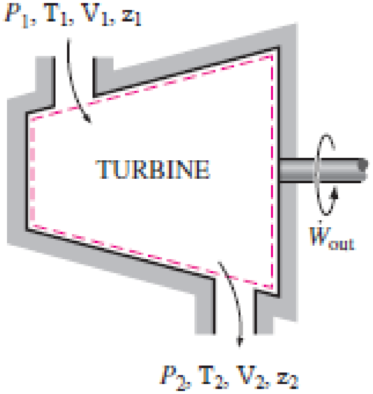
$$\left(\dot{Q}_{in} - \dot{Q}_{out}\right) - \dot{W}_{out} = \dot{m}\left[(h_2 - h_1) + \left(\frac{v_2^2 - v_1^2}{2}\right)\right]$$

For single stream, neglected change in potential energy and adiabatic turbine:

$$\dot{W}_{out} = \dot{m}\left[(h_1 - h_2) + \left(\frac{v_1^2 - v_2^2}{2}\right)\right]$$

4. SOME STEADY-FLOW ENGINEERING DEVICES

➢ Turbine:



- **Energy balance for single stream-*incompressible* fluid flow:**

$$\Delta h = \frac{\Delta p}{\rho}$$

$$\left(\dot{Q}_{in} - \dot{Q}_{out}\right) - \dot{W}_{out} = \dot{m}\left[\left(\frac{p_2 - p_1}{\rho}\right) + \left(\frac{v_2^2 - v_1^2}{2}\right) + g(z_2 - z_1)\right]$$

For single stream and neglected change in potential energy:

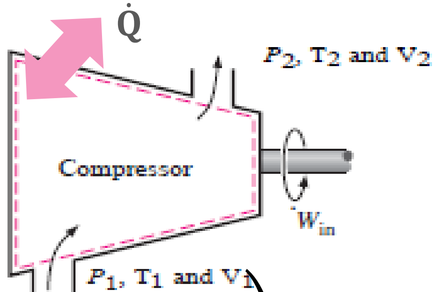
$$\left(\dot{Q}_{in} - \dot{Q}_{out}\right) - \dot{W}_{out} = \dot{m}\left[\left(\frac{p_2 - p_1}{\rho}\right) + \left(\frac{v_2^2 - v_1^2}{2}\right)\right]$$

For single stream, neglected change in potential energy and adiabatic turbine:

$$\dot{W}_{out} = \dot{m}\left[\left(\frac{p_1 - p_2}{\rho}\right) + \left(\frac{v_1^2 - v_2^2}{2}\right)\right]$$

4. SOME STEADY-FLOW ENGINEERING DEVICES

➢ Compressor:



- ***Compressor*** **is a device that delivers power to a compressible fluid.**
- **Energy balance for single stream-*<u>compressible</u>* fluid flow:**

$$\dot{Q}_{in} + \dot{W}_{in} + \dot{m}_{in}\left(h_{in} + \frac{v_{in}^2}{2} + gz_{in}\right) = \dot{Q}_{out} + \underset{\text{Zero}}{\dot{W}_{out}} + \dot{m}_{out}\left(h_{out} + \frac{v_{out}^2}{2} + gz_{out}\right)$$

$$\left(\dot{Q}_{in} - \dot{Q}_{out}\right) + \dot{W}_{in} = \dot{m}\left[(h_2 - h_1) + \left(\frac{v_2^2 - v_1^2}{2}\right) + g(z_2 - z_1)\right]$$

For single stream and neglected change in potential energy:

$$\left(\dot{Q}_{in} - \dot{Q}_{out}\right) + \dot{W}_{in} = \dot{m}\left[(h_2 - h_1) + \left(\frac{v_2^2 - v_1^2}{2}\right)\right]$$

For single stream, neglected change in potential energy and adiabatic compressor:

$$\dot{W}_{in} = \dot{m}\left[(h_2 - h_1) + \left(\frac{v_2^2 - v_1^2}{2}\right)\right]$$

4. SOME STEADY-FLOW ENGINEERING DEVICES

➢ Pump:

- ***Pump*** **is a device that delivers power to an incompressible fluid.**
- **Energy balance for single stream-*incompressible* fluid flow:**

$$\dot{Q}_{\text{in}} + \dot{W}_{\text{in}} + \dot{m}_{\text{in}}\left(h_{\text{in}} + \frac{v_{\text{in}}^2}{2} + gz_{\text{in}}\right) = \dot{Q}_{\text{out}} + \underset{\text{Zero}}{\cancel{\dot{W}_{\text{out}}}} + \dot{m}_{\text{out}}\left(h_{\text{out}} + \frac{v_{\text{out}}^2}{2} + gz_{\text{out}}\right)$$

$$\left(\dot{Q}_{\text{in}} - \dot{Q}_{\text{out}}\right) + \dot{W}_{\text{in}} = \dot{m}\left[\left(\frac{p_2 - p_1}{\rho}\right) + \left(\frac{v_2^2 - v_1^2}{2}\right) + g(z_2 - z_1)\right]$$

For single stream and neglected change in potential energy:

$$\left(\dot{Q}_{\text{in}} - \dot{Q}_{\text{out}}\right) + \dot{W}_{\text{in}} = \dot{m}\left[\left(\frac{p_2 - p_1}{\rho}\right) + \left(\frac{v_2^2 - v_1^2}{2}\right)\right]$$

For single stream, neglected change in potential energy and adiabatic pump:

$$\dot{W}_{\text{in}} = \dot{m}\left[\left(\frac{p_2 - p_1}{\rho}\right) + \left(\frac{v_2^2 - v_1^2}{2}\right)\right]$$

4. SOME STEADY-FLOW ENGINEERING DEVICES

➢ Throttling valve:

- ***Throttling valves*** **are any kind of flow-restricting devices that cause a significant pressure drop in the fluid.**
- ***Throttling valves*** **can be used with compressible or incompressible fluid flow.**
- **Energy balance for single stream fluid flow:**

$$\dot{Q}_{in} + \underset{\text{Zero}}{\cancel{\dot{W}_{in}}} + \dot{m}_{in}\left(h_{in} + \frac{v_{in}^2}{2} + gz_{in}\right) = \dot{Q}_{out} + \underset{\text{Zero}}{\cancel{\dot{W}_{out}}} + \dot{m}_{out}\left(h_{out} + \frac{v_{out}^2}{2} + gz_{out}\right)$$

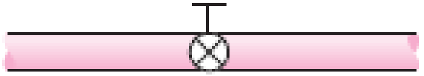
$$\left(\dot{Q}_{in} - \dot{Q}_{out}\right) = \dot{m}\left[(h_2 - h_1) + \left(\frac{v_2^2 - v_1^2}{2}\right) + g(z_2 - z_1)\right]$$

For single stream and neglected change in potential energy:

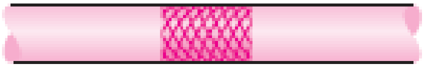
$$\left(\dot{Q}_{in} - \dot{Q}_{out}\right) = \dot{m}\left[(h_2 - h_1) + \left(\frac{v_2^2 - v_1^2}{2}\right)\right]$$

For single stream, neglected change in potential energy and adiabatic:

$$(h_2 - h_1) = \left(\frac{v_1^2 - v_2^2}{2}\right)$$



(*a*) An adjustable valve



(*b*) A porous plug

(*c*) A capillary tube

4. SOME STEADY-FLOW ENGINEERING DEVICES

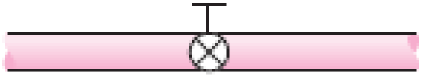
➢ Throttling valve:

For single stream, neglected change in potential energy, adiabatic and constant velocity:

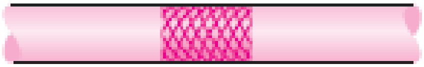
$$\mathbf{h_2 = h_1}$$

For single stream, neglected change in potential energy, adiabatic, constant velocity and ideal gas:

$$\mathbf{T_2 = T_1}$$



(*a*) An adjustable valve



(*b*) A porous plug

(*c*) A capillary tube

4. SOME STEADY-FLOW ENGINEERING DEVICES

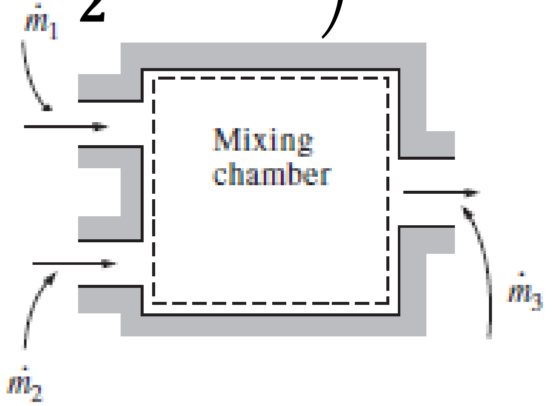
➢ Mixing chamber:

- *Mixing chamber* is a section where the mixing process takes place.
- Energy balance:

$$\dot{Q}_{in} + \dot{W}_{in} + \sum \dot{m}_{in}\left(h_{in} + \frac{v_{in}^2}{2} + gz_{in}\right) = \dot{Q}_{out} + \dot{W}_{out} + \sum \dot{m}_{out}\left(h_{out} + \frac{v_{out}^2}{2} + gz_{out}\right)$$

- Mass balance:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out}$$



For instance, if the mixing chamber has two inlets and one outlet:

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

$$(\dot{Q}_{in} - \dot{Q}_{out}) + (\dot{W}_{in} - \dot{W}_{out}) = \dot{m}_3\left[h_3 + \left(\frac{v_3^2}{2}\right) + gz_3\right] - \dot{m}_1\left[h_1 + \left(\frac{v_1^2}{2}\right) + gz_1\right] - \dot{m}_2\left[h_2 + \left(\frac{v_2^2}{2}\right) + gz_2\right]$$

For neglected potential and kinetic energy, adiabatic and no work interaction:

$$\dot{m}_3 h_3 = \dot{m}_1 h_1 + \dot{m}_2 h_2$$

4. SOME STEADY-FLOW ENGINEERING DEVICES

➢ Heat exchanger:

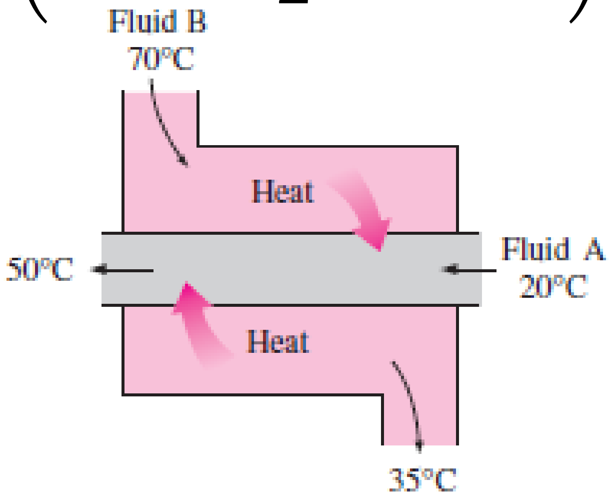
- ***Heat exchangers*** **are devices where two moving fluid streams exchange heat without mixing.**

- **Energy balance:**

$$\dot{Q}_{in} + \underset{\text{Zero}}{\cancel{\dot{W}_{in}}} + \sum \dot{m}_{in} \overbrace{\left(h_{in} + \frac{v_{in}^2}{2} + gz_{in}\right)}^{\theta_{in}} = \dot{Q}_{out} + \underset{\text{Zero}}{\cancel{\dot{W}_{out}}} + \sum \dot{m}_{out} \overbrace{\left(h_{out} + \frac{v_{out}^2}{2} + gz_{out}\right)}^{\theta_{out}}$$

- **Mass balance:**

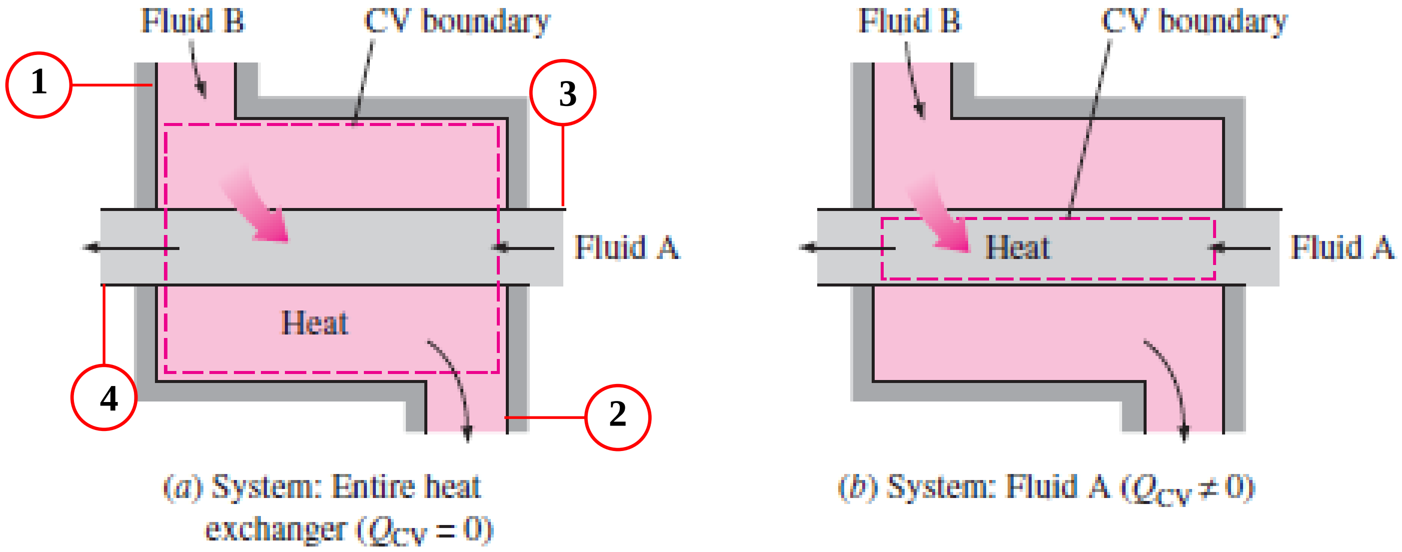
$$\sum \dot{m}_{in} = \sum \dot{m}_{out}$$



4. SOME STEADY-FLOW ENGINEERING DEVICES

➢ Heat exchanger:

The heat transfer associated with a heat exchanger may be zero or nonzero depending on how the control volume is selected.



(*a*) System: Entire heat exchanger ($Q_{CV} = 0$)

(*b*) System: Fluid A ($Q_{CV} \neq 0$)

- **Energy balance:**

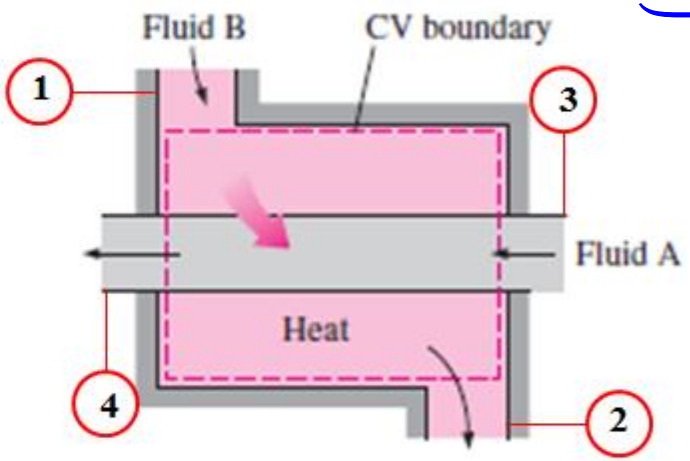
$$\left(\dot{Q}_{in} - \dot{Q}_{out}\right) = \dot{m}_B\theta_2 + \dot{m}_A\theta_4 - \dot{m}_B\theta_1 - \dot{m}_A\theta_3$$

4. SOME STEADY-FLOW ENGINEERING DEVICES

➢ Heat exchanger:

For neglected potential and kinetic energy:

$$\left(\dot{Q}_{in} - \dot{Q}_{out}\right) = \dot{m}_B h_2 + \dot{m}_A h_4 - \dot{m}_B h_1 - \dot{m}_A h_3 = \underbrace{\dot{m}_A\left(h_4 - h_3\right)}_{\dot{Q}_{BA}} - \underbrace{\dot{m}_B\left(h_1 - h_2\right)}_{\dot{Q}_{BA}}$$



For neglected potential and kinetic energy and adiabatic process:

$$\dot{m}_B h_2 + \dot{m}_A h_4 = \dot{m}_B h_1 + \dot{m}_A h_3$$
$$\dot{m}_A\left(h_4 - h_3\right) = \dot{m}_B\left(h_1 - h_2\right) = \dot{Q}_{BA}$$