Lecture 4

The First Law of Thermodynamics

Definition

The first law of thermodynamics, also known as the *conservation of energy principle*, states that:

Energy can be neither created nor destroyed; it can only change forms.

$$\begin{pmatrix}\text{Total Energy}\\ \text{entering the system}\end{pmatrix} - \begin{pmatrix}\text{Total energy}\\ \text{leaving the system}\end{pmatrix} = \begin{pmatrix}\text{Change in the total}\\ \text{energy of the system}\end{pmatrix}$$

$$\underbrace{E_{in} - E_{out}}_{\substack{\text{Net energy transfer}\\ \text{by heat, work and mass}}} = \underbrace{\Delta E_{system}}_{\substack{\text{Change in internal, kinetics}\\ \text{potential, etc., energies}}} \quad (\text{kJ})$$

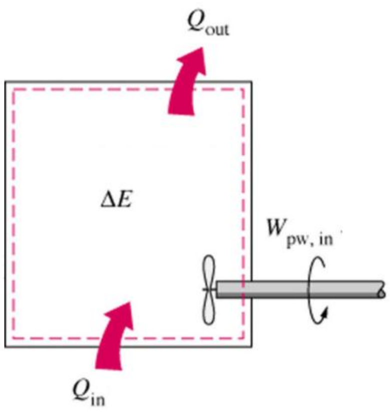
<u>In the rate form, as:</u>

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

Energy Balance for a *Closed System*

- ***Sign Convention 1:*** *No sign convention!*
  Just take care of energies in and out.

$$Q_{in} + W_{in} + E_{in} = Q_{out} + W_{out} + E_{out}$$



- ***Sign Convention 2:*** *Heat added to the system is positive*
Work done by the system is positive

$$(Q_{in} - Q_{out}) + (W_{in} - W_{out}) = \Delta E_{system}$$

$$Q_{net,in} - W_{net,out} = \Delta E_{system}$$

$$\text{or } Q - W = \Delta E$$

- ***For stationary system:*** $\Delta KE = \Delta PE = 0, \ \Delta E = \Delta U$

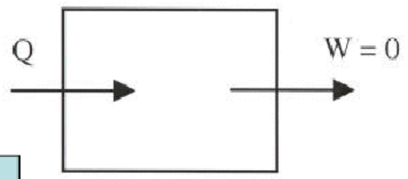
$$\text{The 1st Law: } Q - W = \Delta U$$

A) Constant-Volume Process

The 1st Law: $Q - W = \Delta U$

Where $W = P\Delta V = 0$

$Q = \Delta U$



$$Q = \Delta U = U_2 - U_1 = \int_{T_1}^{T_2} mC_V\,dT \approx mC_V(T_2 - T_1)$$

B) Constant-Pressure Process:

The 1st Law: $Q - W = \Delta U$

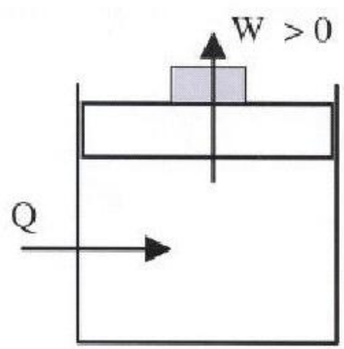
Where $W = P\Delta V$

$Q = P\Delta V + \Delta U$

Since P is a constant: $P\Delta V = \Delta(PV)$

$Q = \Delta(PV) + \Delta U = \Delta(PV + U) = \Delta H$

$$Q = \Delta H$$



$$Q = \Delta H = H_2 - H_1 = \int_{T_1}^{T_2} mC_P\,dT \approx mC_P(T_2 - T_1)$$

C) Isothermal Process:

The 1st Law: $\boldsymbol{Q - W = \Delta U}$

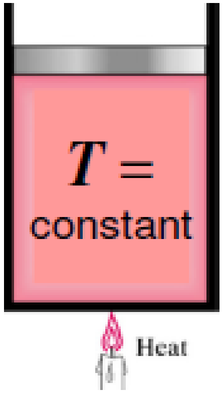
T = constant, then since $U = U(T)$ for ideal gases:

$\Delta U = 0$

$\boldsymbol{Q = W}$

where W = ΔPdV and $PV = mRT$ (ideal gas)

$$Q = W = \int_{V_1}^{V_2} \frac{mRT}{V} dV = mRT \ln\left(\frac{V_2}{V_1}\right)$$

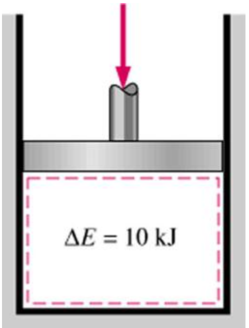


D) Adiabatic Process

The 1st Law: $\boldsymbol{Q - W = \Delta U}$

$\boldsymbol{Q = 0}$

$\boldsymbol{-W = \Delta U}$



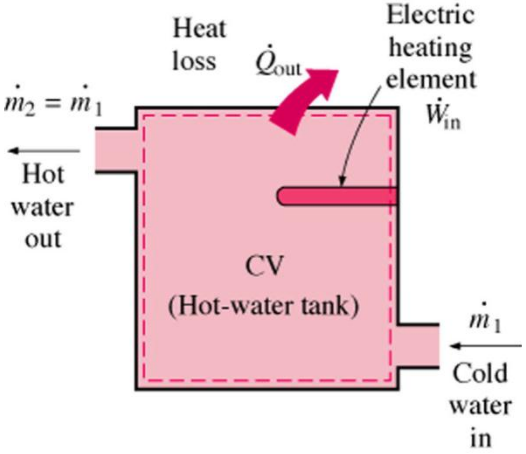
Energy Balance for a Control Volume

- The energy content of a control volume can be changed by *mass flow* as well as *heat* and *work* interactions.

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

- For steady-flow systems ($\Delta E_{system} = 0$):

$$\underbrace{\dot{E}_{in}}_{\substack{\text{Rate of net energy transfer} \\ \text{by heat, work and mass}}} = \underbrace{\dot{E}_{out}}_{\substack{\text{Rate of change in internal,} \\ \text{kinetics, potential, etc., energies}}}$$



- For a general steady-flow system:

$$\dot{Q}_{in} + \dot{W}_{in} + \sum \dot{m}_i\theta_i = \dot{Q}_{out} + \dot{W}_{out} + \sum \dot{m}_e\theta_e \quad \text{or}$$

1st sign convention

$$\dot{Q}_{in} + \dot{W}_{in} + \underbrace{\sum \dot{m}_i\left(h_i + \frac{v_i^2}{2} + gz_i\right)}_{\text{For each inlet}} = \dot{Q}_{out} + \dot{W}_{out} + \underbrace{\sum \dot{m}_e\left(h_e + \frac{v_e^2}{2} + gz_e\right)}_{\text{For each exit}}$$

- Let,

$$\dot{Q} = \dot{Q}_{in} - \dot{Q}_{out} \begin{cases} \dot{Q} > 0, & \text{heat input to the system} \\ \dot{Q} < 0, & \text{heat transfer from the system} \end{cases} \quad \text{and}$$

$$\dot{W} = \dot{W}_{out} - \dot{W}_{in} \begin{cases} \dot{W} > 0, & \text{work output from the system} \\ \dot{W} < 0, & \text{work done on the system} \end{cases}$$

$$\dot{Q} - \dot{W} = \underbrace{\sum \dot{m}_e\left(h_e + \frac{v_e^2}{2} + gz_e\right)}_{\text{For each exit}} - \underbrace{\sum \dot{m}_i\left(h_i + \frac{v_i^2}{2} + gz_i\right)}_{\text{For each inlet}}$$

2nd sign convention

- For single-stream steady-flow systems

$$(\dot{m}_i = \dot{m}_e) \qquad \dot{Q} - \dot{W} = \dot{m}_e\left[h_e - h_i + \frac{V_e^2}{2} - \frac{V_i^2}{2} + g(z_e - z_i)\right]$$

- In terms of *unit mass:*

$$q - w = \frac{\dot{Q}}{\dot{m}} - \frac{\dot{W}}{\dot{m}} = \Delta h + \Delta ke + \Delta pe$$

- If $\Delta K_e = 0$, $\Delta P_e = 0$

$$q - w = \Delta h \quad \text{or}$$

The 1st Law: $Q - W = \Delta H$

❑ Steady-State Engineering devices:-

Some common steady-state devices are:

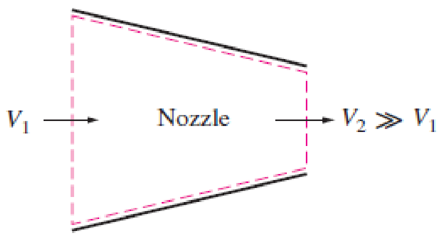
1. Nozzles and diffusers
2. Turbines, Compressors, pumps, and fans
3. Throttles
4. Mixers
5. Heat Exchangers

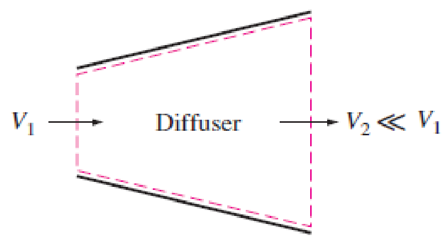
Diffuser and Nozzle:

Nozzles and diffusers are commonly utilized in wind tunnels, jet engines, rockets, space-craft, and even garden hoses.

Nozzle: it is a flow passage of varying cross section area in which the velocity of flow increase in direction of flow.

Diffuser: it is a flow passage of varying cross section area in which the velocity of flow decrease in direction of flow.





Characteristics:

- $\dot{Q} \cong 0$
- $\dot{W} = 0$
- $\Delta pe \cong 0$
- $\Delta ke \neq 0$

$$Q + \sum m_i \left(h_i + \frac{V_1^2}{2} + gZ_i \right) = W + \sum m_e \left(h_e + \frac{V_e^2}{2} + gZ_e \right)$$

$$h_i + \frac{V_1^2}{2} = h_e + \frac{V_e^2}{2}$$

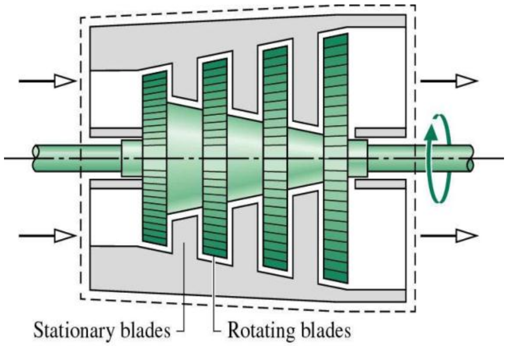
Turbine and Compressor and Pump:

❑ Turbines:-

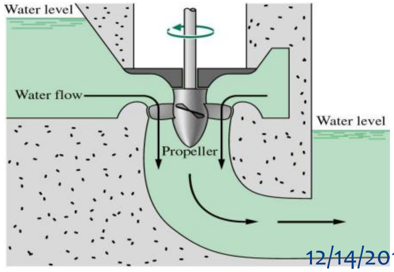
it is a device in which work done or developed as a result of flow of gas or liquid passing through a blades. They are widely used in

- *vapour power plants,*
- gas turbine power plants,
- aircraft engines.

- ***Superheated steam*** or a gas enters the turbine and expands to a lower exit pressure as work is developed. As the fluid passes through the turbine, work is done against the ***blades***, which are attached to the ***shaft***. As a result, the shaft rotates, and the turbine produces work. The work done by turbines is ***positive*** since it is done by the fluid.



- ***In hydraulic turbine***, water falling through the propeller causes the shaft to rotate and work is developed.

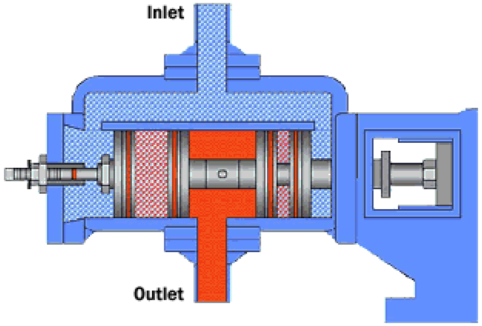


❑ Compressors

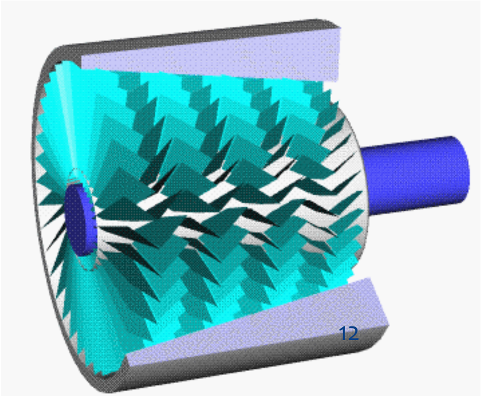
it is a device in which work done on gas passing through them in order to raise the pressure.

➢ ***Different types of compressors are available such as reciprocating, axial, centrifugal, etc..)***

✓ **Reciprocating compressors**



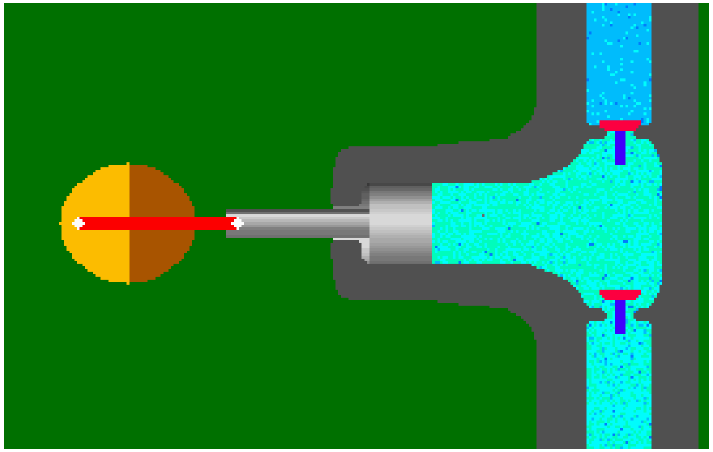
✓ **Axial compressors**



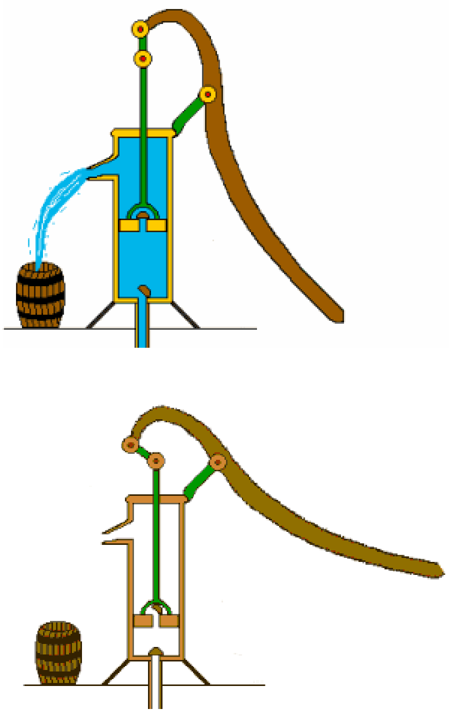
❑ Pumps

it is a device in which the work input is used to change state of the following liquid.

- ***Different types of pumps are available such as reciprocating, piston, axial, centrifugal, peristaltic, etc..)***

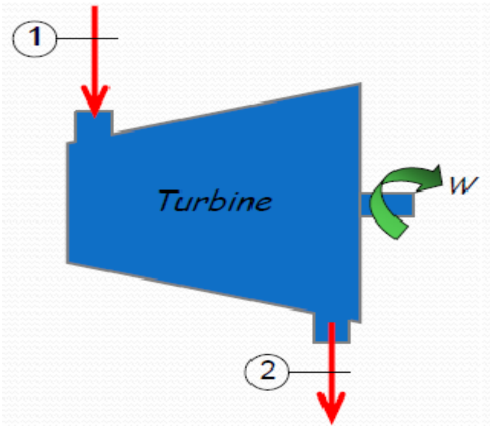


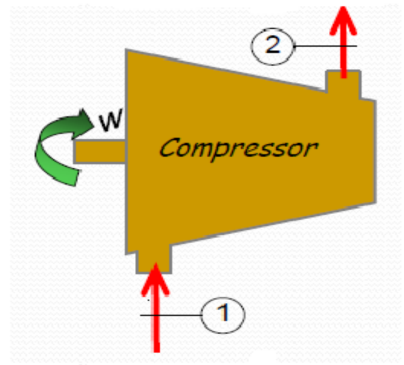
Piston pump

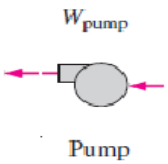


Lift pump

Turbine and Compressor and Pump







Characteristics:

- $\dot{Q} \cong 0$
- $\Delta pe \cong 0$
- $\Delta ke \cong 0$
- $\dot{W}_{out} \ncong 0$

$$Q + \sum \dot{m}_i \left(h_i + \frac{v_1^2}{2} + gZ_i \right) = W + \sum \dot{m}_e \left(h_e + \frac{v_e^2}{2} + gZ_e \right)$$

$$W = \dot{m}_e \left(h_i - h_e \right)$$

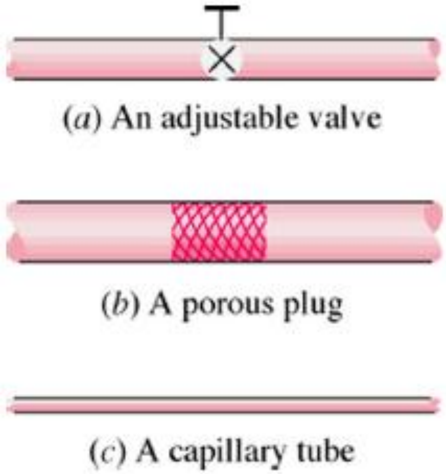
Note:

Turbines are devices that produce work. But ***compressor, pump*** and ***fan*** are devices that require work.

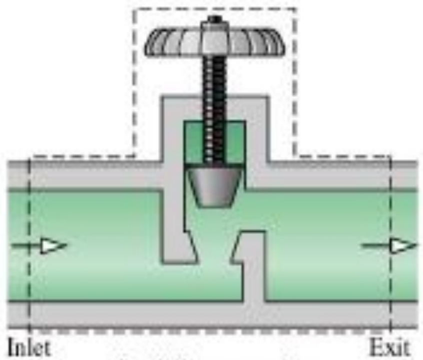
❑ Throttling Valves

it is a device that causes a significant pressure drop in the fluid. But Unlike turbines, they *produce pressure drop* without involving any work.

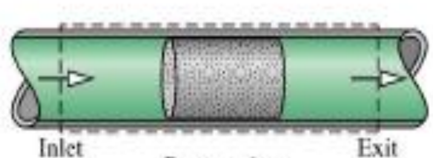
- are *flow-restricting devices* that cause a significant pressure drop in the fluid.
- Unlike turbines, they *produce pressure drop* without involving any work.
- Some familiar examples are:
  - (*a*)-ordinary *adjustable valves*
  - (*b*)-porous plugs
  - (*c*)-capillary tubes



- ***Application:*** *Pressure drop* in fluids is often accompanied by a large *drop in temperature*, and for that reason throttling devices are commonly used in *refrigeration and air conditioning* applications.



Partially open valve



Porous plug

Characteristics:

- $\dot{Q} \cong 0$
- $\Delta pe \cong 0$
- $\Delta ke \cong 0$
- $\dot{W} \cong 0$

$$Q + \sum \dot{m}_i \left(h_i + \frac{v_1^2}{2} + gZ_i \right) = W + \sum \dot{m}_e \left(h_e + \frac{v_e^2}{2} + gZ_e \right)$$

$$h_i = h_e$$

Note:

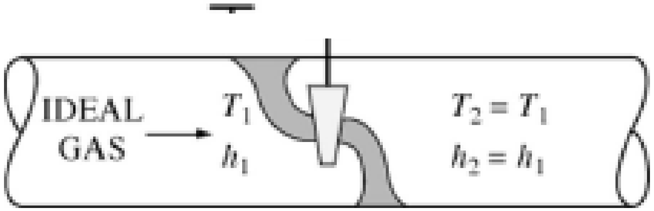
➢During the throttling process, *h of a fluid remains constant.* But *internal and flow energy are converted to each other.*

Internal Energy + Flow Energy = Constant

$$u_1 + P_1 v_1 = u_2 + P_2 v_2 = \text{constant}$$

$$\text{if } P_1 v_1 > P_2 v_2 \Rightarrow u_1 < u_2 \Rightarrow T_1 < T_2; \quad T \uparrow$$

$$\text{if } P_1 v_1 < P_2 v_2 \Rightarrow u_1 > u_2 \Rightarrow T_1 > T_2; \quad T \downarrow$$



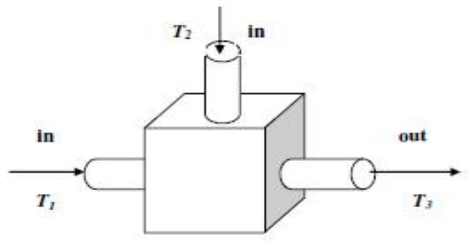
➢If the flow energy ***Pv increases during a process, It can do*** so at the expense of internal energy *u. As a result, u* decreases, which is usually accompanied by a drop in *T.*

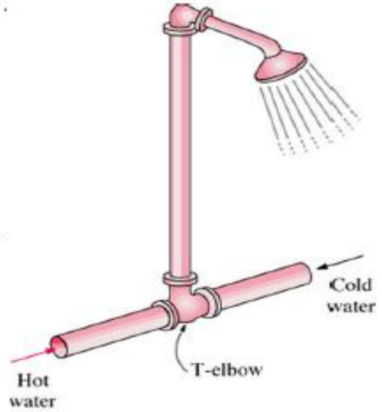
➢If the product *Pv decreases, u and T of a fluid will increase* during a throttling process

Mixing Chambers

➢Mixer chambers (a pot, vessel, section,….) are devices where two moving fluid streams exchange heat due to mixing.

➢An ordinary *T-elbow or Y-elbow in a shower, for example, can* serve as the mixing chamber for the cold and hot water steams.





Characteristics:

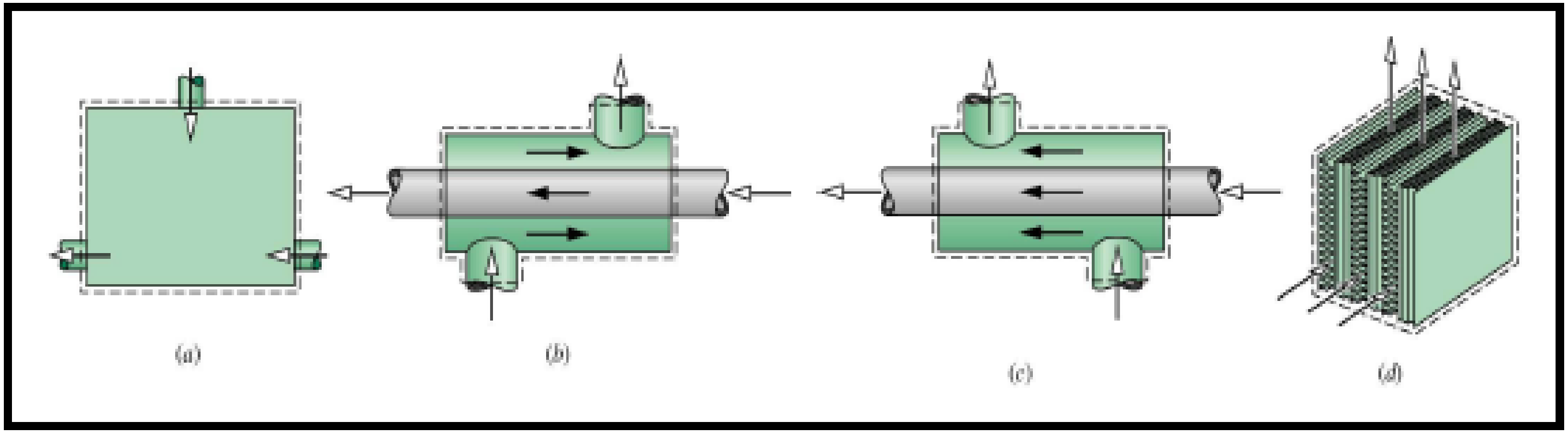
- $\Delta m_{CV} = 0$
- $\Delta E_{CV} = 0$
- $\Delta pe \cong 0$
- $\Delta ke \cong 0$
- $\dot{Q} = 0$
- $\dot{W} = 0$

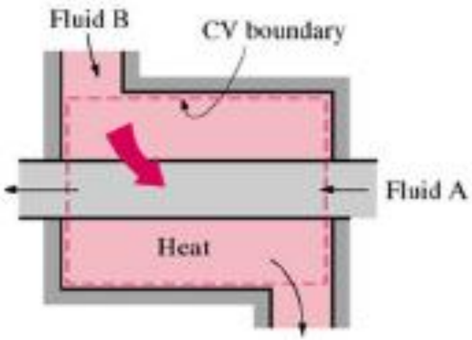
$$Q + \sum \dot{m}_i \left(h_i + \frac{v_1^2}{2} + gZ_i \right) = W + \sum \dot{m}_e \left(h_e + \frac{v_e^2}{2} + gZ_e \right)$$

$$\sum \dot{m}_i h_i = \sum \dot{m}_e h_e$$

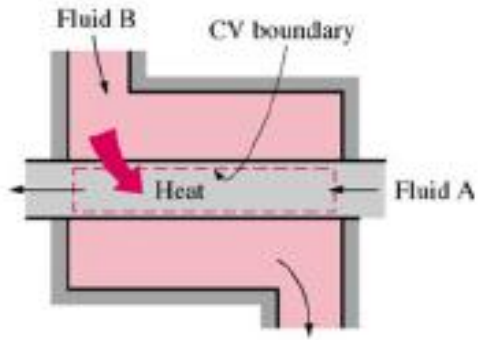
Heat Exchangers

- Heat Exchangers are devices where two moving fluid streams exchange heat without mixing.
- The simplest form of a heat exchanger is a *double tube* (also called *tube-and shell) heat exchanger (b,c).*
- It is composed of two concentric pipes of different diameters. One fluid flows
in the inner pipe, and the other in the annular space between the two pipes.
- Heat is transferred from the hot fluid to the cold one through the wall separating them.





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



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

Characteristics:

- $\Delta m_{CV} \cong 0$
- $\dot{W} = 0;$
- $\Delta pe \cong 0$
- $\Delta ke \cong 0$
  - $(a)\ \dot{Q}_{CV} \cong 0$
  - $(b)\ \dot{Q}_{CV} \neq 0$

$$Q + \sum m_i^{\cdot} \left(h_i + \frac{v_1^2}{2} + gZ_i \right) = W + \sum m_e^{\cdot} \left(h_e + \frac{v_e^2}{2} + gZ_e \right)$$

$$(a)\ \ m_{A,in}\, h_{A,in} + m_{B,in}\, h_{B,in} = m_{A,out}\, h_{A,out} + m_{B,out}\, h_{B,out}$$

$$(b)\ \ Q^{\cdot} = m_{A,out}\, h_{A,out} - m_{A,in}\, h_{A,in}$$