# Chemical Engineering (Thermodynamics I) (UCH305)

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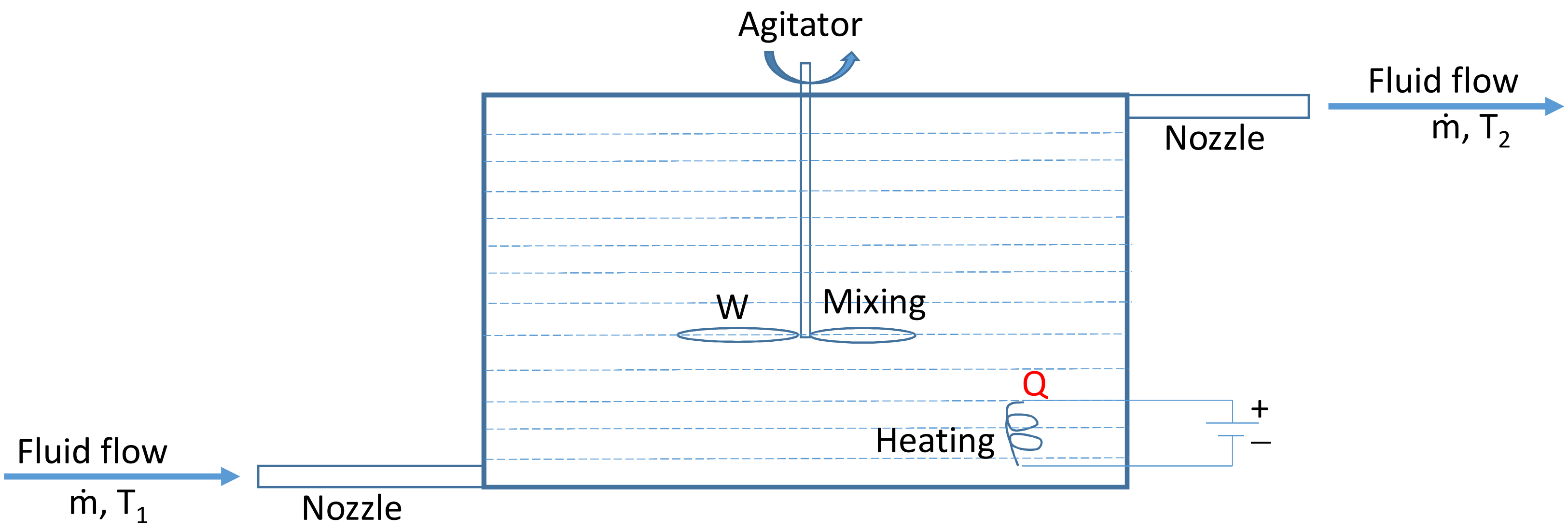
# Lecture 14

# First Law of Thermodynamics
# Open systems
# (Control volume systems)

# Open system



Agitator
Fluid flow
$\dot{m}$, $T_2$
Nozzle
W
Mixing
Q
+
–
Heating
Fluid flow
$\dot{m}$, $T_1$
Nozzle

# Mass and Energy analysis of Control Volumes

- **Mass Flow Rate:**

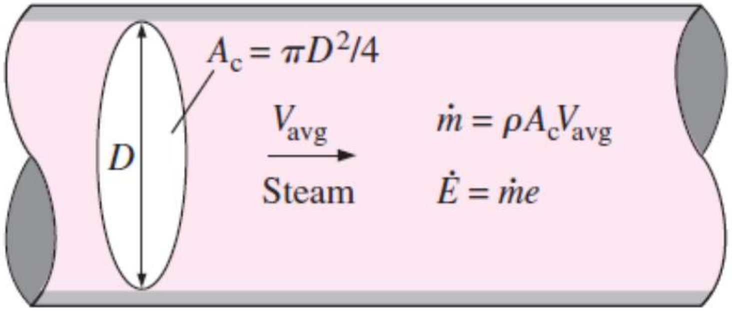
  $$\dot{m} = \rho \times v_{avg} \times A_{c,s} = \rho \times v \times A$$

  Where:

  $\rho$ = density, kg/m$^3$.

  $v_{avg}$ = average velocity, m/s

  $A_{c,s}$ = cross-sectional area, m$^2$. ($\pi r^2 = \pi d^2/4$)




- **Volume Flow Rate:**

  $$\dot{V} = v_{avg} \times A_{cs} = v \times A$$

- The mass and volume flow rates are related by:

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

# Conservation of Mass Principle (mass balance equations)

- 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 $\Delta t$ is equal to the net change (increase or decrease) in the total mass within the control volume during $\Delta t$.*

$$\boxed{\begin{pmatrix}\text{Total mass entering} \\ \text{the CV during } \Delta t\end{pmatrix} - \begin{pmatrix}\text{Total mass leaving} \\ \text{the CV during } \Delta t\end{pmatrix} = \begin{pmatrix}\text{Net change in mass} \\ \text{within the CV during } \Delta t\end{pmatrix}}$$

  - $m_{in} - m_{out} = \Delta m_{CV}$ (kg)

Where,

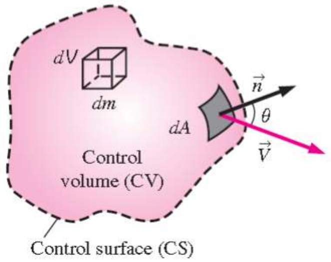
$\Delta m_{CV} = (m_{final} - m_{initial})$ is the change in the mass of the control volume during the process (accumulation of mass),

$\Delta t$ = change in time,

$CV$ = control volume.

- It can also be expressed in *rate form* as:
  - $\dot{m}_{in} - \dot{m}_{out} = dm_{CV}/dt$ (kg/s)

- Consider a control volume of arbitrary shape, as shown in Figure.




- The mass of a differential volume *dV* within the control volume is
  - $dm = \rho\, dV$

- The total mass within the control volume at any instant in time *t* is determined by integration to be:
  - *Total mass within the CV:* $\boxed{m_{CV} = \int_{CV} \rho\, dV}$

- Then the time rate of change of the amount of mass (kg/s) within the control volume can be expressed as:

  - *Rate of change of mass within the CV:*

$$\frac{dm_{CV}}{dt} = \frac{d}{dt}\int_{CV} \rho \, dV$$

- Mass flow rate be expressed as (kg/s):

$$\frac{d}{dt}\int_{CV} \rho \, dV = \sum_{in} \dot{m} - \sum_{out} \dot{m}$$

*or*

$$\frac{dm_{CV}}{dt} = \sum_{in} \dot{m} - \sum_{out} \dot{m}$$

# Steady-Flow systems

- Devices which operate for long periods of time under the same conditions they are classified as *steady-flow devices/systems*.

- Processes involving such devices can be represented reasonably well by a somewhat idealized process, called the **steady-flow process,**

## Steady-flow devices (Open systems / Control volumes)

- Nozzles
- Compressors
- Turbines
- Throttling valves
- Mixers
- Heaters
- Heat exchangers
- Reactors, etc.

# 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).

$$\boxed{\cancelto{0}{\frac{dm_{CV}}{dt}} = \sum_{in} \dot{m} - \sum_{out} \dot{m}}$$

$$\boxed{0 = \sum_{in} \dot{m} - \sum_{out} \dot{m}}$$

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

# *For single-stream steady-flow systems*

- Devices such as nozzles, diffusers, turbines, compressors, and pumps involve a single stream (only one inlet and one outlet).

- For these cases, we denote the inlet state by the subscript 1 and the outlet state by the subscript 2, and drop the summation signs.

- Then the mass flow rate equation reduces for *single-stream steady-flow systems*, to

$$\dot{m}_{in} = \dot{m}_{out} \longrightarrow \rho_1 v_1 A_1 = \rho_2 v_2 A_2$$

# Special Case: Incompressible Flow

- The conservation of mass relations can be simplified even further when the fluid is incompressible, which is usually the case for liquids. (*Density change is negligible*)

$$\therefore \qquad \rho_1 = \rho_2$$

- Cancelling the density from both sides of the general steady-flow relation gives:
  - *Steady, incompressible flow:*

$$\boxed{\sum_{in} \dot{V} = \sum_{out} \dot{V}} \quad (m^3/s)$$

- For single-stream steady-flow systems it becomes:
  - *Steady, incompressible flow (single stream):* $\boxed{\dot{V}_1 = \dot{V}_2 \quad \rightarrow \quad v_1 A_1 = v_2 A_2}$
- *Where*
  - *$\dot{V}$ = Volumetric flow rate, $m^3/s$*
  - *$v$ = velocity, m/s*

# 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.

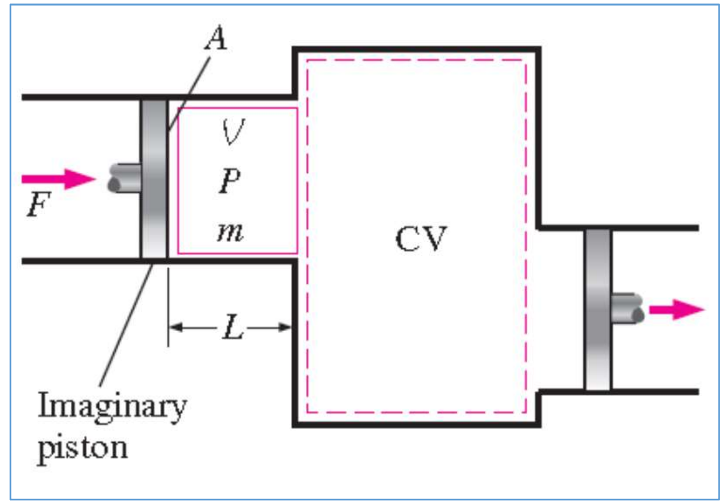
- This work is known as the ***flow work***, or ***flow energy***, and is necessary for maintaining a continuous flow through a control volume.

# Flow work

- To obtain a relation for flow work, consider a fluid element of volume $V$ as shown in Fig.

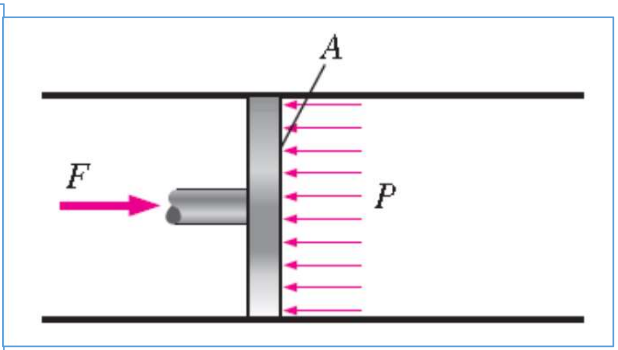
- The fluid immediately upstream, forces this fluid element to enter the control volume; thus, it can be regarded as an imaginary piston.

- The fluid element can be chosen to be sufficiently small so that it has uniform properties throughout.

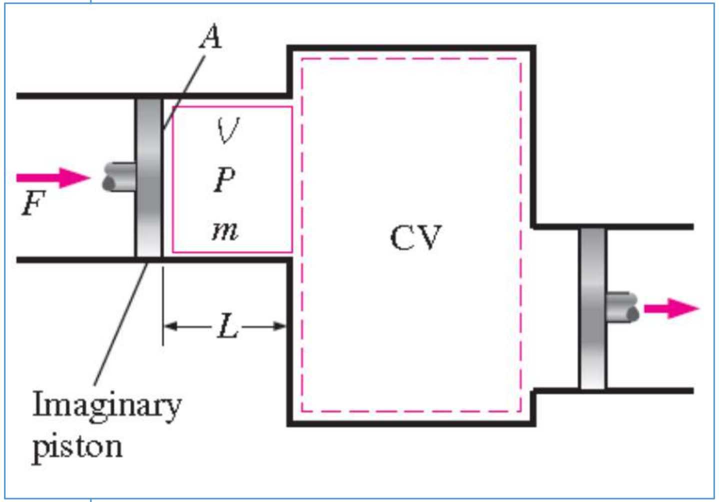


- If the fluid pressure is $p$ and the cross-sectional area of the fluid element is $A$ (Figure), the force applied on the fluid element by the imaginary piston is:

$$F = p \times A \qquad (N)$$




- To push the entire fluid element into the control volume, this force must act through a distance $L$.




- Thus, the work done in pushing the fluid element across the boundary (i.e., the flow work) is:

$$W_{\text{flow}} = F \times L = (p \times A) \times L = p \times V \qquad (kJ)$$

- The flow work per unit mass is obtained by dividing both sides of this equation by the mass of the fluid element:
  - $w_{work} = p \times v \quad (kJ/kg)$

- The flow work relation is the same whether the fluid is pushed into or out of the control volume.

- It is interesting that unlike other work quantities,
  - flow work is expressed in terms of properties.

- In fact, it is the product of two properties of the fluid.

- For that reason, some people view it as a *combination property* (like enthalpy) and refer to it as:
  - *flow energy*, *convected energy*, or *transport energy* instead of *flow work*.

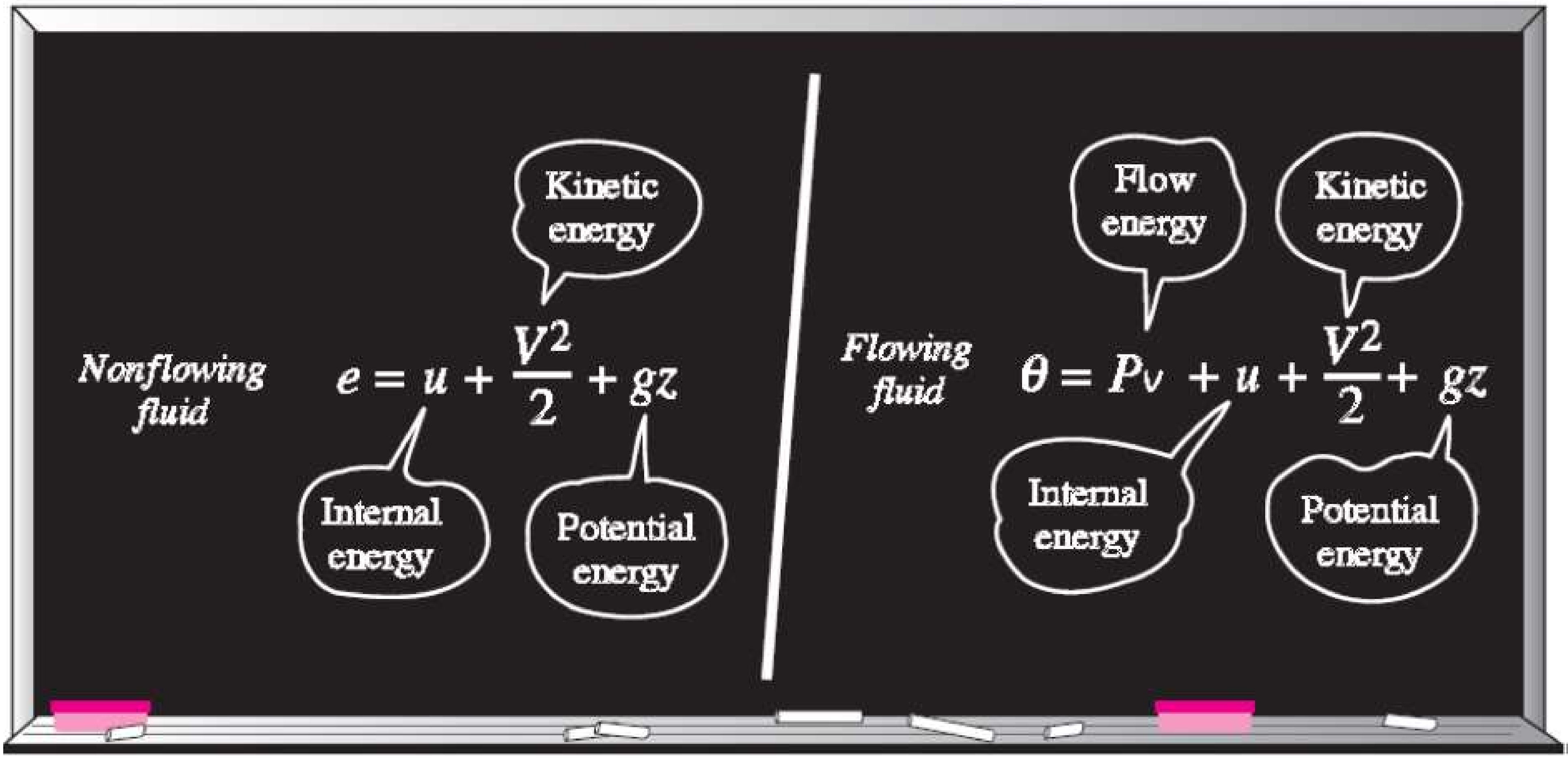
# Total Energy of a Flowing Fluid (*E*)

- The total energy (***E***) of a simple compressible system consists of three parts:
  - internal,
  - kinetic, and
  - potential energies

- On a unit-mass basis for ***closed system***, it is expressed as:

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

- where $v$ is the velocity and $z$ is the elevation of the system relative to some external reference point.


Nonflowing fluid
$e = u + \frac{V^2}{2} + gz$
Kinetic energy
Internal energy
Potential energy
Flowing fluid
$\theta = Pv + u + \frac{V^2}{2} + gz$
Flow energy
Kinetic energy
Internal energy
Potential energy

- The fluid entering or leaving a ***control volume (open system)*** possesses an additional form of energy—the *flow energy, pv* (as already discussed).

- Then the total energy of a ***flowing fluid*** on a unit-mass basis (denoted by $\theta$) becomes:
  - $\theta = (p \times v) + e$
  - $\theta = (p \times v) + (u + ke + pe)$

- But the combination $(pv + u)$ has been previously defined as the enthalpy $h$.

- So the relation reduces to: $$\boxed{\theta = h + ke + pe = h + \frac{v^2}{2} + gz \qquad (kJ/kg)}$$

- By using the enthalpy instead of the internal energy to represent the energy of a flowing fluid, one does not need to be concerned about the flow work.
- The energy associated with pushing the fluid into or out of the control volume is automatically taken care of by enthalpy.
- In fact, this is the main reason for defining the property enthalpy.
- From now on, the energy of a fluid stream flowing into or out of a control volume is represented by Equation, and no reference will be made to flow work or flow energy.

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

# Energy Transport by Mass

- The $\theta$ is total energy per unit mass, the total energy of a flowing fluid of mass $m$ is simply $m\theta$, provided that the properties of the mass $m$ are uniform, where
  - $\theta = (p \times v) + e$
  - $\theta = (p \times v) + (u + ke + pe)$
- Also, when a fluid stream with uniform properties is flowing at a mass flow rate of $\dot{m}$, the rate of energy flow with that stream is $\dot{m}\theta$.
- That is,
  - *Amount of energy transport: for given time Δt*

$$E_{mass} = m\theta = m\left(h + \frac{v^2}{2} + gz\right) \qquad (kJ)$$

  - *Rate of energy transport: (why because, J/s = W)*

$$\dot{E}_{mass} = \dot{m}\,\theta = \dot{m}\left(h + \frac{v^2}{2} + gz\right) \qquad (kW)$$

- When the kinetic and potential energies of a fluid stream are negligible, as is often the case, these relations simplify to:
  - *Amount of energy transport:* $$\boxed{E_{mass} = m \times h}$$
  - *Rate of energy transport:* $$\boxed{\dot{E}_{mass} = \dot{m} \times h}$$

# References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***Thank you for your Patience***