

Engineering Thermodynamics I

Lecture 4

First Law of Thermodynamics and Energy

Lecturer: Dr. Melaku Desta

Lecture learning outcomes:

At the end of this lecture, you will be able to:

- i. Understand the first law of thermodynamics and its implications for energy conservation.
- ii. Define specific heats, internal energy, and enthalpy, and explain their significance in thermodynamic systems.
- iii. Distinguish between specific heats of ideal gases, solids, and liquids, including their practical applications.
- iv. Apply the first law of thermodynamics to control volumes in different engineering scenarios.
- v. Solve thermodynamic problems using formulas and concepts introduced in this lecture.

Content

1. Internal Energy and Enthalpy
2. Specific Heats
3. Internal Energy, Enthalpy, and Specific Heats of Ideal Gases
4. Internal Energy, Enthalpy, and Specific Heats of Solids and Liquids
5. The First Law and the Control Volume
6. Flow Work and the Energy of a Flowing Fluid
7. Some Steady-Flow Engineering Devices

Summary

References

1. Internal Energy and Enthalpy

Internal Energy

- **Internal energy (U)** represents the total **microscopic energy** contained within a system due to the motion and interactions of its molecules. It includes:
 - **Kinetic energy**: from the movement of molecules and atoms, such as their vibrations, rotations, and translations.
 - **Potential energy**: arising from the interactions between particles, like chemical bonds and intermolecular forces.
- **Internal energy** is a state function, meaning it depends only on the current state of the system (temperature, pressure, phase, etc.), not on the path taken to reach that state.

1. Internal Energy and Enthalpy

Cont...

Internal Energy

- The internal energy includes some complex forms of energy show up due to **translation**, **rotation** and **vibration** of molecules.
- It is designated by **U** and it is **extensive property**.
- Or per unit mass as, specific internal energy,

$$u = \frac{U}{m}$$

1. Internal Energy and Enthalpy

Cont...

Enthalpy

- Enthalpy represents the total energy of a system, including its **internal energy** and the **energy required to displace its surroundings** to make space for the system.
- It is another **extensive property** which has a unit of energy and it is denoted by **H**.
- The enthalpy is a convenient grouping of the **internal energy, pressure, and volume** and is given by:

$$H = U + PV$$

Where:

U is the internal energy of the system,

P is the pressure of the system,

V is the volume of the system.

1. Internal Energy and Enthalpy

Cont...

Enthalpy

- The enthalpy per unit mass is,

$$h = \frac{H}{m}$$

- The **change in enthalpy** (ΔH) is equivalent to the heat added to or released by the system.

For example:

- A positive ΔH indicates that the process **absorbs heat** (endothermic).
- A negative ΔH shows that the process **releases heat** (exothermic).

1. Internal Energy and Enthalpy

Cont...

Enthalpy

- Mathematically, **enthalpy** can be defined as:

$$h = u + Pv$$

$$Q_{12} = (U_2 - U_1) + W_{12}$$

$$W_{12} = \int_1^2 PdV = P \int_1^2 dV = P(V_2 - V_1)$$

$$W_{12} = PV_2 - PV_1$$

$$Q_{12} = (U_2 - U_1) + PV_2 - PV_1$$

$$Q_{12} = (U_2 + PV_2) - (U_1 + PV_1)$$

$$Q_{12} = H_2 - H_1$$

2. Specific Heat

- Specific heat is defined as; the energy required to raise the temperature of a unit mass of a substance by one degree [1].
- It is an **intensive property** of a substance that will enable us to compare the energy storage capability of various substances. The unit is:

$$kJ/Kg^{\circ}C \quad \text{or} \quad kJ/Kg K$$

- In thermodynamics, we are interested in two kinds of specific heats:
 - specific heat at **constant volume**, and
 - specific heat at **constant pressure**

2. Specific Heat

Cont...

The specific heat at constant volume C_v

- It can be viewed as the energy required to raise the temperature of the unit mass of a substance by one degree as the volume is maintained constant.
- Here the boundary work is zero because the volume is constant.
- From first law: $\delta Q = dU$
- Per unit mass: $\delta q = du, \quad \delta q = C_v dT$

$$C_v dT = du$$
$$C_v = \left(\frac{du}{dT} \right)_v$$

2. Specific Heat

Cont...

The specific heat at constant pressure C_p

- It can be viewed as the energy required to raise the temperature of the unit mass of a substance by one degree as the pressure is maintained constant.
- From first law: $\delta Q = dU + PdV = d(U + PV) = dH$
- Per unit mass: $\delta q = dh, \quad \delta q = C_p dT$

$$C_p dT = dh$$

$$C_p = \left(\frac{dh}{dT} \right)_p$$

3. Internal Energy, Enthalpy, and Specific Heats of Ideal Gases

- We defined an **ideal gas** as a gas whose temperature, pressure, and specific volume are related by

$$Pv = RT \quad \text{and, } h = u + Pv \text{ then, } h = u + RT$$

- From the **specific heat** relation: $du = C_v dT$

$$u_2 - u_1 = \int C_v dT$$

- Or taking average value of specific heat for narrow temperature difference: $u_2 - u_1 = C_{avg,v} (T_2 - T_1)$

3. Internal Energy, Enthalpy, and Specific Heats of Ideal Gases Cont...

$$Pv = RT$$

and, $h = u + Pv$ then, $h = u + RT$

- From the **specific heat** relation:

$$dh = C_p dT$$

$$h_2 - h_1 = \int C_p dT$$

- Or taking average value of specific heat for narrow temperature difference

$$h_2 - h_1 = C_{avg,p} (T_2 - T_1)$$

Relation between C_p and C_v for Ideal Gases

$$h = u + RT, \quad dh = du + RdT$$

- Replacing dh by $C_p dT$ and du by $C_v dT$, we have

$$C_p dT = C_v dT + RdT$$

$$C_p = C_v + R$$

- At this point, we introduce another ideal-gas property called the **specific heat ratio**

K, defined as: $K = \frac{C_p}{C_v}$ $C_p = KC_v$ $KC_v = C_v + R$

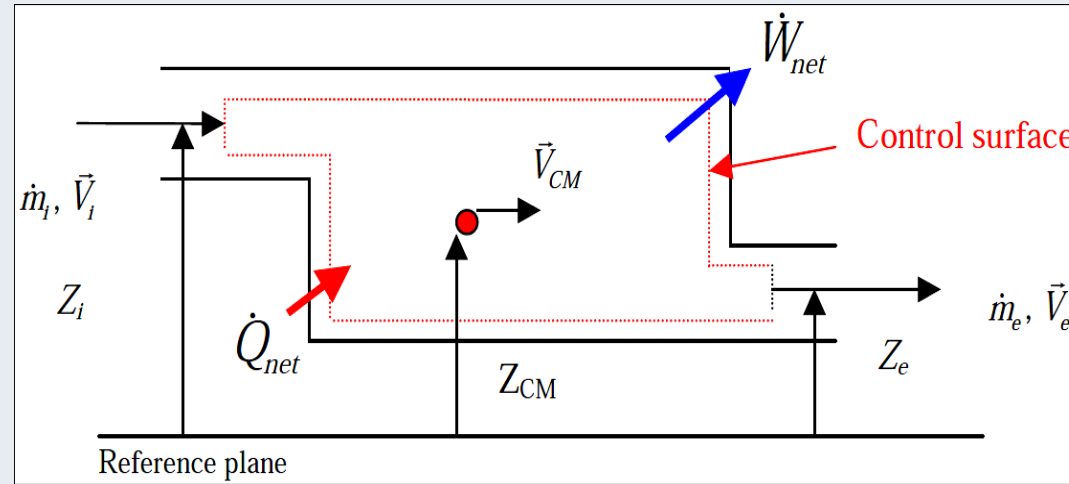
$$C_v = \frac{R}{K - 1} \quad C_p = \frac{C_p}{K} + R \quad C_p = \frac{K}{K - 1} R$$

4. Internal Energy, Enthalpy, and Specific Heats of Solids and Liquids

- A substance whose specific volume (or density) is constant is called an **incompressible substance** [2].
- The specific volumes of **solids** and **liquids** essentially remain constant during a process. Therefore, liquids and solids can be approximated as **incompressible substances**.
- It can be mathematically shown that the **constant-volume** and **constant-pressure** specific heats are identical for incompressible substances.
- The specific heat can be expressed as

$$C_p = C_v = C$$

5. The First Law and the Control Volume



- The conservation of **mass** and the conservation of **energy** principles for open systems or control volumes apply to systems having mass crossing the system boundary or control surface.

5. The First Law and the Control Volume

Cont...

- In addition to the heat transfer and work crossing the system boundaries, **mass carries energy** with it as it crosses the system boundaries.
- Hence the conservation of mass principle can be used to relate mass which entering and leaving a system.
- The net mass transfer to or from a control volume during a process (at time interval t) is equal to the net change (increase or decrease) in the total mass within the control volume during that process (t) [1]. That is,

$$\left(\begin{array}{l} \text{Total mass Entering} \\ \text{the CV during } \Delta t \end{array} \right) - \left(\begin{array}{l} \text{Total mass Leaving} \\ \text{the CV during } \Delta t \end{array} \right) = \left(\begin{array}{l} \text{Net Change in mass} \\ \text{within the CV during } \Delta t \end{array} \right)$$

5. The First Law and the Control Volume

Cont...

- Thermodynamic processes involving control volumes can be considered in two groups: **steady-flow processes** and **unsteady-flow processes**.

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

$$\dot{m}_{in} - \dot{m}_{out} = \frac{dm_{cv}}{dt} \quad (kg/s)$$

- And we know that,

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

Steady State Processes

- The flow through a control volume is at steady state if, “the property of the substance at a given position within or at the boundaries of the control volume **do not change with time**” [3].
- During a steady-flow process, the total amount of mass contained within a control volume does not change with time ($m_{CV} = \text{constant}$).
- Although energy and mass may flow into and out of the system, the rates of inflow and outflow are balanced, and the system's state remains constant.

Steady State Processes

Key characteristics of steady state processes include:

- **No accumulation:** There is no net change in mass, energy, or other properties within the control volume.
- **Time invariance:** The system's properties (pressure, temperature, velocity, etc.) at a given point remain constant over time.
- **Mass and energy conservation:** The incoming and outgoing flows of mass and energy are equal, ensuring equilibrium.

Steady State Processes

$$\dot{m}_{in} - \dot{m}_{out} = \frac{dm_{CV}}{dt} \quad \frac{dm_{CV}}{dt} = \Delta m_{CV} = 0$$

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

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

$$\rho_{in} V_{in} = \rho_{out} V_{out}$$

$\rho_{in} = \rho_{out}$, incompressible assumption

$$V_{in} = V_{out}$$

$$\vec{v}_{in} A_{in} = \vec{v}_{out} A_{out}$$

Unsteady State Process

- Unsteady state processes, also known as **transient processes**, are those in which the properties of a system **change with time**.
- The properties within the control volume change with time but remain uniform at any instant of time.
- Unlike steady state processes, the system is not in equilibrium, and the variables such as temperature, pressure, mass flow, or energy vary until the system reaches a new equilibrium or steady state.

Key Features of Unsteady State Processes

- **Time Dependence:** The properties and behavior of the system are functions of time.
- **Dynamic Changes:** Mass, energy, or momentum can accumulate or deplete in the system.
- **Control Volume:** The first law of thermodynamics (energy balance) must consider changes over time. For example:

Example:- filling and emptying processes where most of the cases average value of properties must be used

6. Flow Work and The Energy of a Flowing Fluid

- **Flow work**, also known as **flow energy**, is the work required to move a fluid into or out of a control volume in thermodynamic systems [4].
- 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 concept is especially important when analyzing systems with mass transfer, such as turbines, compressors, and pipes.

6. Flow Work and The Energy of a Flowing Fluid

Cont...

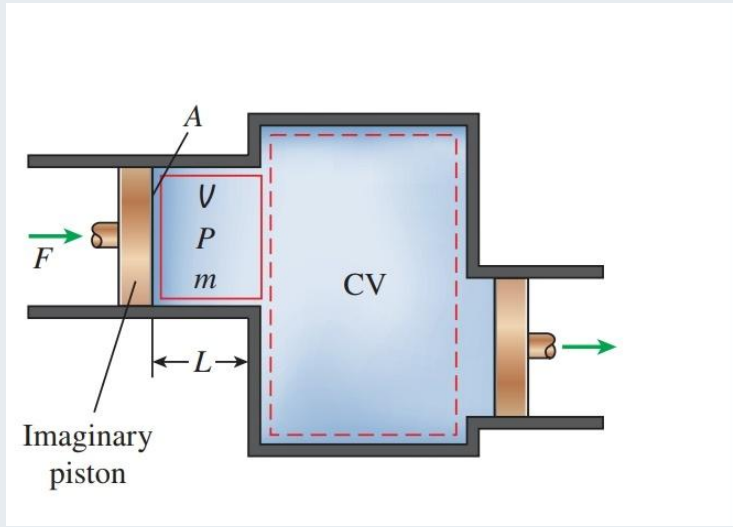


Figure 1: Schematic for Flow work

url: <https://i.sstatic.net/1vwGW.jpg>

$$F = PA$$

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

$$w_{flow} = Pv$$

$$w_{flow,in} = P_i v_i \quad \text{and} \quad w_{flow,exit} = P_e v_e$$

$$W_{flow,in} = (P_i v_i) m_i \quad \text{and} \quad W_{flow,exit} = (P_e v_e) m_e$$

$$W_{flow} = (P_e v_e) m_e - (P_i v_i) m_i$$

$$W = W_{flow} + W_{CV}$$

6. Flow Work and The Energy of a Flowing Fluid

Cont...

Development of energy balance

- The general representation of the first law of thermodynamics

$$Q_{12} = W_{12} + E_2 - E_1$$

- The first law for open system will also have the same form, but

$$W_{12} = W_{flow} + W_{CV}$$

E = Internal Energy + Kinetic Energy + Potential Energy

$$E = U + KE + PE$$

$$e = u + ke + pe = u + \frac{V^2}{2} + gz$$

Development of energy balance

- The fluid entering or leaving a control volume possesses an additional form of energy, the flow energy Pv .
- Then the total energy of a flowing fluid on a unit-mass basis (denoted by θ) becomes

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

- But the combination $Pv + u$ has been previously defined as the enthalpy h . So the relation in the above equation reduces to:

$$\theta = h + ke + pe = h + \frac{V^2}{2} + gz \quad \left(\frac{kJ}{kg}\right)$$

6. Flow Work and The Energy of a Flowing Fluid

Cont...

- For inlet

$$e_i + P_i v_i = u_i + \frac{V_i^2}{2} + gz_i + P_i v_i \qquad e_i + P_i v_i = h_i + \frac{V_i^2}{2} + gz_i$$

- For outlet

$$e_e + P_e v_e = h_e + \frac{V_e^2}{2} + gz_e$$

- General equation

$$E_{in} - E_{out} = \frac{dE_{system}}{dt} = 0$$

$$Q_{in} + W_{in} + \sum_{in} m\theta = Q_{out} + W_{out} + \sum_{out} m\theta$$

$$Q_{in} + W_{in} + \sum_{in} m\left(h_i + \frac{V_i^2}{2} + gz_i\right) = Q_{out} + W_{out} + \sum_{out} m\left(h_e + \frac{V_e^2}{2} + gz_e\right)$$

6. Flow Work and The Energy of a Flowing Fluid

Cont...

- In such cases, it is common practice to assume heat to be transferred into the system (heat input) at a rate of Q , and work produced by the system (work output) at a rate of W , and then solve the problem.
- The first-law or energy balance relation in that case for a general steady-flow system becomes:

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

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

6. Flow Work and The Energy of a Flowing Fluid

Cont...

- When the fluid experiences negligible changes in its kinetic and potential energies:

That is, $ke = 0$, and

$$pe = 0,$$

the energy balance equation is reduced further to:

$$q - w = h_2 - h_1$$

7. Some Steady-Flow Engineering Devices

i. Nozzles and Diffusers

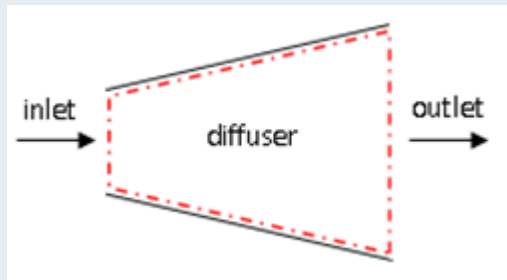
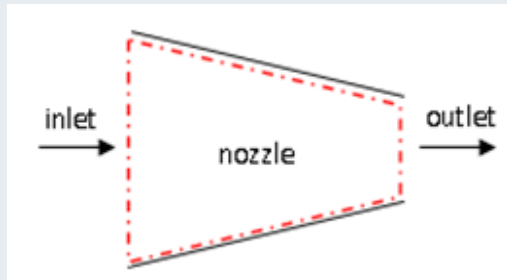
- Nozzles and diffusers are commonly utilized in jet engines, rockets, spacecraft, and even garden hoses.
 - A **nozzle** is a device that *increases the velocity of a fluid* at the expense of pressure.
 - A **diffuser** is a device that *increases the pressure of a fluid* by slowing it down.

i. Nozzles and Diffusers

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

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

$$E_{in} = E_{out}$$



$$Q_{net} + \sum_{in} m \left(h_i + \frac{V_i^2}{2} + gz_i \right) = W_{net} + \sum_{out} m \left(h_e + \frac{V_e^2}{2} + gz_e \right)$$

$$m_i \left(h_i + \frac{V_i^2}{2} \right) = m_e \left(h_e + \frac{V_e^2}{2} \right)$$

$$V_e = \sqrt{2(h_i - h_e) + V_i^2}$$

Figure 2: Nozzle and Diffuser

url: <https://qph.cf2.quoracdn.net/main-qimg-c58eea4e44590bb35e57d9081ae10470>

7. Some Steady-Flow Engineering Devices

Cont...

Example:

1. Air enters an adiabatic nozzle steadily at 250 kPa, 150°C, and 25 m/s and leaves at 100 kPa and 150 m/s. The inlet area of the nozzle is 60 cm².

Determine: (a) the mass flow rate through the nozzle,
(b) the exit temperature of the air, and
(c) the exit area of the nozzle.

Given:

There is one inlet and one exit, so $m_1 = m_2 = m$

The gas constant of air is $0.287 \text{ kPa} \cdot \text{m}^3/\text{kg K}$

$$C_{p, \text{air}} = 1.02 \text{ kJ/kg}^\circ\text{C}$$

7. Some Steady-Flow Engineering Devices

Cont...

Solution:

Using the ideal gas relation: $P_1 v_1 = RT_1$

$$v_1 = \frac{RT_1}{P_1} = \frac{\left(0.287 \text{ kPa} \cdot \frac{\text{m}^3}{\text{kgK}}\right)(423\text{K})}{250\text{kPa}} = 0.485 \text{ m}^3/\text{kg}$$

$$m = \frac{1}{v_1} A_1 V_1 = \frac{1}{0.485 \text{ m}^3/\text{kg}} (0.006\text{m}^2)(25 \text{ m/s}) = \mathbf{0.309 \text{ kg/s}}$$

$$\mathbf{m = 0.309 \text{ kg/s}}$$

From the energy balance of nozzles,

$$\left(m \left(h_1 + \frac{V_1^2}{2}\right)\right) = \left(m \left(h_2 + \frac{V_2^2}{2}\right)\right)$$

7. Some Steady-Flow Engineering Devices

Cont...

Since $Q = W = 0$,

$$0 = h_2 - h_1 + \frac{V_2^2 - V_1^2}{2}$$

$$0 = C_{p,avg}(T_2 - T_1) + \frac{V_2^2 - V_1^2}{2}$$

$$0 = 1.02 \text{ kJ/kgK}(T_2 - 150^\circ\text{C}) + \frac{(150 \text{ m/s})^2 - (25 \text{ m/s})^2}{2}$$

Therefore, **$T_2 = 139.3^\circ\text{C}$**

The specific volume of the air at the nozzle exit is

$$v_2 = \frac{RT_2}{P_2} = \frac{(0.287 \text{ kPa} \cdot \frac{\text{m}^3}{\text{kgK}})(412\text{K})}{100\text{kPa}} = 1.182 \text{ m}^3/\text{kg}$$

7. Some Steady-Flow Engineering Devices

Cont...

Therefore, $m = \frac{1}{v_2} A_2 V_2$

$$0.309 \text{ kg/s} = \frac{1}{1.182 \text{ m}^3/\text{kg}} A_2 (150 \text{ m/s})$$

$$A_2 = 0.00243 \text{ m}^2 = 24.3 \text{ cm}^2$$

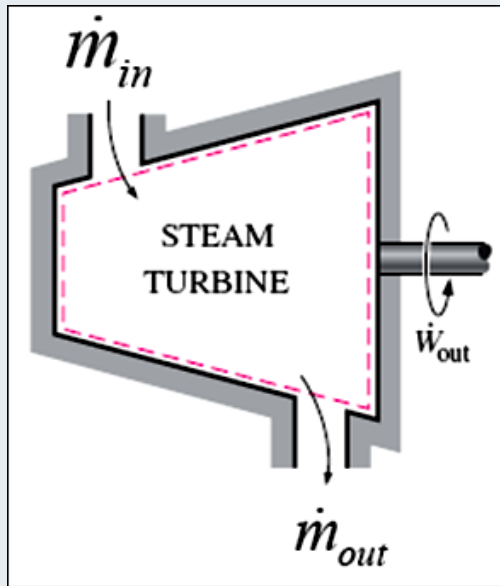
ii. Turbines

- In steam, gas, or hydroelectric power plants, the device that drives the electric generator is the turbine.
- 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.

7. Some Steady-Flow Engineering Devices

Cont...

ii. Turbines



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

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

$$E_{in} = E_{out}$$

$$Q_{net} + \sum_{in} m \left(h_i + \frac{V_i^2}{2} + gz_i \right) = W_{net} + \sum_{out} m \left(h_e + \frac{V_e^2}{2} + gz_e \right)$$

$$m_i h_i = m_e h_e + W_{out}$$

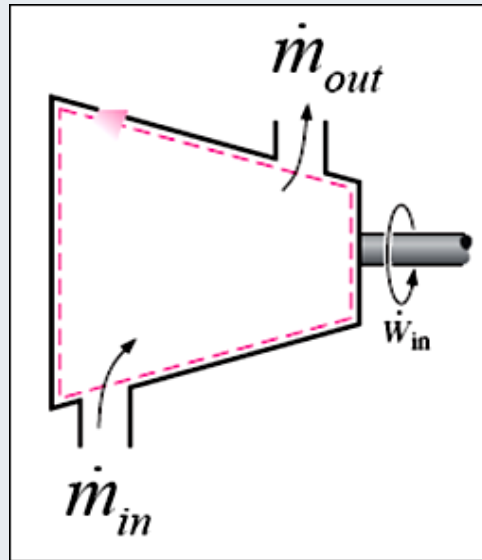
$$W_{out} = m(h_i - h_e)$$

Figure 3: A Steam Turbine [1]

iii. Compressors

- Compressors, as well as fans, are devices used to increase the pressure of a fluid.
- Work is supplied to these devices from an external source through a rotating shaft.

iii. Compressors



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

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

$$Q_{net} + \sum_{in} m \left(h_i + \frac{V_i^2}{2} + gz_i \right) = W_{net} + \sum_{out} m \left(h_e + \frac{V_e^2}{2} + gz_e \right)$$

$$-W_{net} = m(h_e - h_i)$$

$$-W_{net} = m(h_e - h_i)$$

$$W_{net} = m(h_i - h_e)$$

Figure 4: An Adiabatic Compressor [1]

iv. Pumps

The work required when pumping an incompressible liquid in an adiabatic steady-state, steady-flow process is given by

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

The enthalpy difference can be written as

$$h_2 - h_1 = (u_2 - u_1) + [(Pv)_2 - (Pv)_1]$$

iv. Pumps

- The pumping process for an incompressible liquid is essentially isothermal, and the internal energy change is approximately zero.
- Since $v_2 = v_1 = v$ the work input to the pump becomes:

$$-W = m \left[v(P_2 - P_1) + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1) \right]$$

$$-W = m[v(P_2 - P_1)]$$

$$w_{in,pump} = m[v(P_2 - P_1)]$$

v. Throttling Valves

- Throttling valves are any kind of flow-restricting devices that cause a significant pressure drop in the fluid.
- The pressure drop in the fluid is often accompanied by a large drop in temperature, and for that reason throttling devices are commonly used in refrigeration and air-conditioning applications [5].

v. Throttling Valves



$$Q_{net} + \sum_{in} m \left(h_i + \frac{V_i^2}{2} + gz_i \right) = W_{net} + \sum_{out} m \left(h_e + \frac{V_e^2}{2} + gz_e \right)$$

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

$$m_i h_i = m_e h_e$$

$$h_i = h_e$$

Figure 5: Throttling Valve

[url: https://i.ytimg.com/vi/bhsTyRyCEf0/maxresdefault.jpg](https://i.ytimg.com/vi/bhsTyRyCEf0/maxresdefault.jpg)

vi. Mixing Chambers

- The mixing of two fluids occurs frequently in engineering applications. The section where the mixing process takes place is called a mixing chamber.
- The ordinary shower is an example of a mixing chamber.

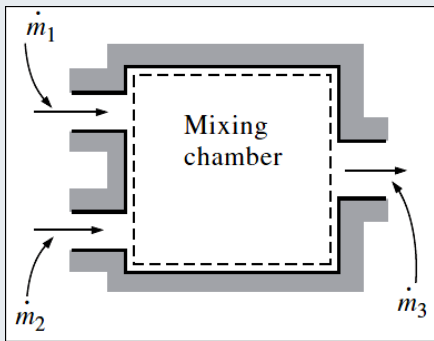


Figure 6: Mixing Chamber [1]

$$\sum m_{in} = \sum m_{out}$$

$$m_1 + m_2 = m_3$$

$$m_2 = m_3 - m_1$$

$$E_{in} = E_{out}$$

$$Q_{net} + \sum_{in} m \left(h_i + \frac{V_i^2}{2} + gz_i \right) = W_{net} + \sum_{out} m \left(h_e + \frac{V_e^2}{2} + gz_e \right)$$

$$m_1 h_1 + m_2 h_2 = m_3 h_3$$

$$m_1 h_1 + (m_3 - m_1) h_2 = m_3 h_3$$

$$m_1 (h_1 - h_2) = m_3 (h_3 - h_2)$$

$$m_1 = m_3 \frac{(h_3 - h_2)}{(h_1 - h_2)}$$

Summary

- Internal energy (U) is the energy due to molecular motion, while enthalpy ($H=U+PV$) represents the total heat content in a system.
- Specific Heats: Specific heat at constant volume (C_v) and constant pressure (C_p); for ideal gases, they are related by $C_p - C_v = R$,
- For Ideal Gases: Internal energy and enthalpy are temperature-dependent only; changes in these properties are calculated using specific heats.
- For Liquids and Solids: Internal energy and enthalpy are less sensitive to temperature changes compared to gases, and specific heat values often remain approximately constant.
- The first law of thermodynamics applies to control volumes, accounting for energy transfer via heat, work, and mass flow, including flow work (PV) and kinetic and potential energy contributions.
- Key steady flow devices include nozzles, turbines, compressors, heat exchangers, and pumps, each serving specific purposes like energy transfer, pressure control, or velocity alteration.

References

- [1]. Thermodynamics – An Engineering Approach, Cengel Y A.,Bole M A., McGraw-Hill Education, 8th edition 2015.
- [2]. Energy and Exergy Efficiencies, Ibrahim Dincer, Comprehensive Energy Systems, 2018, Pages 263-339, <https://doi.org/10.1016/B978-0-12-809597-3.00123-1>
- [3]. First Law of Thermodynamics, Bahman Zohuri, Physics of Cryogenics, 2018, Pages 119-163, <https://doi.org/10.1016/B978-0-12-814519-7.00005-7>.
- [4]. Thermodynamics of Multiphase Systems, Amir Faghri, Yuwen Zhang, Transport Phenomena in Multiphase Systems, 2006, Pages 107-176, <https://doi.org/10.1016/B978-0-12-370610-2.50007-6>
- [5]. Fundamentals of Engineering Thermodynamics, Michael J. Moran, Howard N. Shapiro, Daisie D. Boettner, Margaret B. Bailey - (2010, Wiley) - libgen.lc

Thank you !