Closed Systems in Thermodynamics

Introduction

A **closed system** in thermodynamics is a system where *mass is fixed* (no matter enters or leaves), but *energy can cross the system boundary* in the form of heat or work. This is the foundation for analyzing energy conservation, processes, and cycles in engineering.

Key Concepts

- The First Law
- Work
- Heat
- Energies
- Efficiency

Definitions

- **Closed System:** A system where mass remains constant, but energy may cross the boundary.
- **Work (W):** Energy transfer associated with a force acting through a distance. It is *organized* energy transfer.
- **Heat (Q):** Energy transfer due to temperature difference. It is *disorganized* energy transfer.
- **Internal Energy (U):** Microscopic energy associated with molecular motion and interactions.

The First Law of Thermodynamics

For a closed system, the energy balance is:

$$\Delta E_{system} = Q + W$$

where:

$$\Delta E_{system} = \Delta U + \Delta KE + \Delta PE$$

- Q: heat transferred into system (positive if into system).
- W: work done by system (positive if system does work).
- ΔU: change in internal energy.
- ΔKE: change in kinetic energy.
- ΔPE: change in potential energy.

Usually, we will neglect Kinetic and Potential energies. However, there are some cases in which we won't (Like a pump raising liquid, or calculating velocities through tubes).
After neglecting those energies, we get the classic equation:

$$\Delta U = Q + W$$

Work

The work of a process will always be defined as:

$$W = \int_{V_1}^{V_2} P\,dV$$

Except there are different cases:

- **Irreversible Work (Constant P_{ext}:**
$$W = -P_{ext}\Delta V$$
- **Isothermal Ideal Gas:**
$$W = nRT\ln\left(\frac{V_2}{V_1}\right)$$
- **Polytropic Process ($PV^n = C$):**
$$W = \frac{P_2V_2 - P_1V_1}{1-n}, \quad n \neq 1$$
- **Adiabatic Ideal gas:**
$$W = \Delta U = nC_v\Delta T = \frac{P_2V_2 - P_1V_1}{1 - \frac{C_p}{C_v}}$$

Heat Transfer

Heat transfer (Q) can be a lot more fluid in how it's calculated. Usually we try to limit Q, and so we can assume that the system is insulated ($Q = 0$) Or we can say that our given process happens so quick that $Q = 0$.

- Adiabatic (Insulated): $Q = 0$
- Isothermal: $\Delta U = 0$ So $Q = -W$
- Constant Pressure (Open to atmosphere): $Q = \Delta H = nC_p\Delta T$
- Constant Volume (Rigid Container): $W = 0$ so $Q = \Delta U = nC_v\Delta T$

Energies

(i) Internal Energy
  - A collection of macroscopic energies (Potential and Kinetic), at the microscopic level.
  - Typically we use this energy most.
  - Directly related to C_v

(ii) Kinetic Energy
  - We will mostly neglect this.
  - We can use this for nozzles and turbines, anything with high speeds where it can't be neglected.
  - $KE = \frac{1}{2}mv^2$

(iii) Potential Energy
  - Also usually neglected.
  - We can use this for pumps and different systems with water
  - $PE = mgh$

(iv) Enthalpy
  - Enthalpy is the energy needed for a given system to occupy that space.
  - Don't really care in closed systems, our matter isn't changing.

Efficiency

No real world system is reversible, as it would take infinite time. Even getting close to being fully reversible is usually a waste of our time. The thing about reversible systems is that they maximize work, which is what we want. So, usually in irreversible systems, we will have a net energy loss. We like to quantify that with efficiency:

$$\eta = \frac{W_{actual}}{W_{reversible}}$$

Or, if we do it with Q:

$$\eta = \frac{Q_{actual}}{Q_{reversible}}$$

Example Problem

Consider a piston–cylinder assembly that contains 2.5 L of an ideal gas at 30ºC and 8 bar. The gas reversibly expands to 5 bar.

1. Write an energy balance for this process (you may neglect changes in potential and kinetic energy).
   (i) The First Law of Thermodynamics states that energy balances should take the form: $\mathbf{\Delta U = W + Q}$ Where ΔU is the change in internal energy, W is the Work done by the system, and Q is the heat added to the system.
2. Suppose that the process is done isothermally. What is the change in internal energy, ΔU, for the process? What is the work done, W, during the process? What is the heat transferred, Q?
   (i) We know that the process is isothermal, meaning $\Delta T = 0$ and the process will stay at 30ºC and we know that $\mathbf{\Delta U = 0}$ for isothermal processes.
   (ii) For reversible processes, we know that:

$$W = -\int_{V_1}^{V_2} P_{ext}\, dV \tag{1}$$

   With the Ideal Gas assumption we can turn this into:

$$W = -nRT \int_{V_1}^{V_2} \frac{dV}{V} \tag{2}$$

   We are given V_1, T, and P_1 to which we can find n:

$$n = \frac{PV}{RT} = 0.79\ mol \tag{3}$$

   Then we will solve for V_2:

$$V_2 = \frac{nRT}{P} = 4.9\ L \tag{4}$$

   Now we are finally able to solve for W:

$$W = nRTln\left(\frac{V_1}{V_2}\right) = -13.39\ bar \cdot L = -\mathbf{1339.24\ J} \tag{5}$$

   (iii) For isothermal processes, we know that $W = -Q$, so we know $\mathbf{Q = 1339.24}$

Recap

Closed systems are mass-conserving but allow energy transfer as heat or work. The first law provides a universal energy balance. Understanding the different forms of work and heat is essential for applying thermodynamics to reactors, engines, and industrial processes.