Chapter 22

Heat & Thermodynamics

Heat drifts from warm to cold by nature's claim,
Work trades with warmth, yet leaves no cycle same,
Entropy marks the arrow time must take,
From order born, all paths to balance wake

Thermodynamics deals with heat, work, temperature, and the laws governing energy transfer and transformation. It provides a macroscopic description of physical systems and is independent of microscopic details.

22.1 Thermal Concepts

22.1.1 Temperature

Temperature is a measure of the thermal state of a system and determines the direction of heat flow.

Two systems are in thermal equilibrium if they have the same temperature.

22.1.2 Heat

Heat is energy transferred between systems due to a temperature difference.

The amount of heat Q required to raise the temperature of a substance is

$$Q = mc\Delta T$$

where m is the mass, c the specific heat capacity, and ΔT the change in temperature.

22.2 Thermal Expansion

Most substances expand when heated.

22.2.1 Linear Expansion

The increase in length of a solid is given by

$$\Delta L = \alpha L_0 \Delta T$$

where α is the coefficient of linear expansion.

22.2.2 Volume Expansion

The change in volume is

$$\Delta V = \beta V_0 \Delta T$$

where β is the coefficient of volume expansion.

22.3 Heat Transfer

Heat transfer occurs by conduction, convection, and radiation.

22.3.1 Conduction

For one-dimensional steady-state conduction, Fourier's law is

$$\frac{dQ}{dt} = -kA\frac{dT}{dx}$$

where k is the thermal conductivity.

22.3.2 Radiation

Thermal radiation emitted by a body is given by Stefan–Boltzmann law

$$P = \sigma A T^4$$

where σ is the Stefan–Boltzmann constant.

22.4 Thermodynamic Systems

A thermodynamic system is a specified quantity of matter or region of space.

Systems may be classified as

- Isolated
- Closed
- Open

22.5 Zeroth Law of Thermodynamics

If two systems are each in thermal equilibrium with a third system, then they are in thermal equilibrium with each other.

This law provides the basis for temperature measurement.

22.6 First Law of Thermodynamics

The first law expresses conservation of energy for thermodynamic processes.

For an infinitesimal process

$$dQ = dU + dW$$

where dU is the change in internal energy and dW is the work done by the system.

For a gas undergoing volume change

$$dW = p\,dV$$

22.6.1 Special Thermodynamic Processes

Isothermal Process For an ideal gas at constant temperature

$$pV = \text{constant}$$

Adiabatic Process For a process with no heat exchange

$$pV^{\gamma} = \text{constant}$$

where γ is the ratio of specific heats.

22.7 Second Law of Thermodynamics

The second law introduces the concept of irreversibility.

22.7.1 Kelvin–Planck Statement

It is impossible to construct a cyclic heat engine that converts all absorbed heat into work.

22.7.2 Clausius Statement

Heat cannot spontaneously flow from a colder body to a hotter body.

22.7.3 Entropy

Entropy S is defined through

$$dS = \frac{dQ_{\text{rev}}}{T}$$

For an isolated system

$$\Delta S \geq 0$$

22.8 Heat Engines and Refrigerators

A heat engine operates between a hot reservoir at temperature T_h and a cold reservoir at T_c.

The efficiency of a heat engine is

$$\eta = \frac{W}{Q_h}$$

For a reversible Carnot engine

$$\eta_{\text{max}} = 1 - \frac{T_c}{T_h}$$

22.9 Third Law of Thermodynamics

As the temperature approaches absolute zero, the entropy of a perfect crystal approaches zero.

22.10 Closing Remarks

Thermodynamics provides universal laws governing energy, heat, and irreversibility. These principles apply across physics, chemistry, engineering, and the natural sciences, forming a cornerstone of classical an