

Pre-university Physics Remedial Program

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Chapter 7. Heat and Thermodynamics

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Temperature and Heat

Thermodynamics

- **Thermodynamics:** is a science of the relationship between heat, work, temperature, and energy.
- In broad terms, Thermodynamics deals with the transfer of energy from one system to another and from one form to another.
- In thermodynamics, one usually considers both **thermodynamic systems** and their **environments**.
- A typical thermodynamic system is a definite quantity of gas enclosed in a cylinder with a sliding piston that allows the volume of gas to vary.
- But in general a thermodynamic system is a quantity of matter of fixed identity that is the subject of study and it may be solid, liquid or gas.
- The surrounding is the environment that is around a system and in thermal contact with it.

Temperature

The concept of Temperature

- Temperature: the property that determines whether an object is in thermal equilibrium with other objects.
- It is measure of average molecular kinetic energy of a substance.
- **Temperature scales:** Any physical property that depends consistently and reproducibly on temperature can be used as the basis of a thermometer.
- Example: volume of liquid (basis for alcohol and mercury thermometer), dimension of solid, pressure of the gas at constant volume, volume of the gas at constant pressure.
- Thermometers measure temperature according to well-defined scales of measurement.
- Temperature scales are created by identifying two reproducible temperatures. The freezing and boiling temperatures of water at standard atmospheric pressure are commonly used.

Temperature

Temperature Scale

	$^{\circ}\text{F}$	$^{\circ}\text{C}$	K
Boiling point of water	212	100	373
Freezing point of water	32	0	273
Freezing point of dry ice (CO_2)	-109	-78	195
Boiling point of nitrogen	-321	-196	77
Absolute zero	-460	-273	0

- Exercise: Derive the equations that relate these temperature scale.
- Example: If the ice-point and the steam-point temperatures on an unknown scale X are 50°X and 200°X , respectively, then what is the reading in $^{\circ}\text{X}$ for a temperature of 60°C ?

The Concept of Heat, Work and internal energy

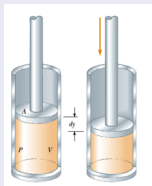
Heat(Q) and Work(W)

- **Heat(Q):** is the spontaneous flow of energy into or out of a system caused by a difference in temperature between the system and its surroundings.
- or it is flow of energy between two objects whose temperatures are different.
- a body never contains heat. Rather, heat can be identified only as it crosses the boundary. Thus, heat is a transient phenomenon.
- Heat is a microscopic form of energy transfer involving large number of particles; the exchange of energy occurs due to the individual interactions of the particles.
- **Work (W):** is a non-spontaneous energy transfer into or out of a system due to force acting through a displacement.
- Work takes many forms, moving a piston, or stirring, or running an electrical current through a resistance.

The Concept of Heat, Work and internal energy

Heat and Work

- At equilibrium, the gas occupies a volume V and exerts a uniform pressure P on the cylinder's walls and on the piston.
- If the piston has a cross-sectional area A , the force exerted by the gas on the piston is $F=PA$.
- Now let us assume that we push the piston inward and compress the gas quasi-statically



- As the piston is pushed downward by an external force $F = -F\hat{j}$, through a displacement of $dr = dy\hat{j}$. The work done on the gas is,
$$dW = F \cdot dr = -F\hat{j} \cdot dy\hat{j} = -PA dy = -PdV \Rightarrow W = - \int_{V_i}^{V_f} PdV$$

The Concept of Heat, Work and internal energy

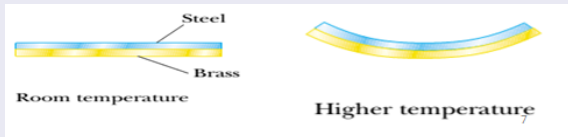
Internal energy (U)

- **Internal Energy:** is the energy associated with the random, disordered motion of the microscopic components-atoms and molecules.
- Any bulk kinetic energy of the system due to its motion through space is not included in its internal energy.
- Internal energy includes kinetic energy of translation, rotation, and vibration of molecules, potential energy within molecules, and potential energy between molecules.
internal energy = thermal energy + bond energy
- Thermal energy can be interpreted as that part of the internal energy associated with random motion of molecules and, therefore, related to temperature.
- Bond energy is the inter molecular potential energy.
- Internal energy changes can also occur in the absence of temperature changes.

Thermal Expansion

Linear Thermal Expansion (1D)

- **Thermal Expansion:** the increase in size of substance due to heat.
- **Linear Thermal Expansion (1D):** The increase in length Δl of a solid depends on initial length l_o and change in temperature ΔT .
- Hence, $\Delta l = \alpha l_o \Delta T \Rightarrow l = l_o(1 + \alpha \Delta T)$
- Where proportionality constant, α is called coefficient of linear expansion.
- **A bimetallic strip:** It consists of two thin strips of dissimilar metals bonded together. As the temperature of the strip increases, the two metals (Example: $\alpha_{steel} = 1.2 \times 10^{-5} \text{K}^{-1}$ and $\alpha_{brass} = 1.9 \times 10^{-5} \text{K}^{-1}$) expand by different amounts and the strip bends.



Thermal Expansion

Area (surface) Expansion (2D)

- **Areal Expansion:** the change in area, ΔA of solid depend on initial area, A_o and the change in temperature, ΔT .
- Hence, $\Delta A = \beta A_o \Delta T \Rightarrow A = A_o(1 + \beta \Delta T)$
- Where proportionality constant, $\beta = 2\alpha$ is called coefficient of area expansion.

Volume Expansion(3D)

- **Volume Expansion:** the change in volume, ΔV of solid depend on initial volume, V_o and the change in temperature, ΔT .
- Hence, $\Delta V = \gamma V_o \Delta T \Rightarrow V = V_o(1 + \gamma \Delta T)$
- Where proportionality constant, $\gamma = 3\alpha$ is called coefficient of volume expansion.
- Exercise 1: Metal A has a coefficient of linear expansion that is three times the coefficient of linear expansion of metal B. How does their β compare?

Specific Heat and Latent Heat

Specific Heat(c)

- **The quantity of heat, Q** required to change the temperature of a body of mass m by ΔT is proportional to both the mass and the change in temperature. Mathematically,
$$Q \propto m\Delta T \Rightarrow Q = mc\Delta T$$
- Where the proportionality constant, c is called specific heat capacity (Specific heat)
- **Specific heat capacity (specific heat):** the amount of heat required to raise the temperature of a unit mass of any substance through a unit degree.
- It has SI unit is of $J/kg \cdot K = J/kg \cdot ^\circ C$
- The amount of heat required to change the temperature of n moles of a substance, usually for gases, by ΔT is given by $Q = n c \Delta T$.
- **Heat capacity(C):** is defined as the amount of heat energy required to raise the temperature of a substance by $1^\circ C$. i.e. $Q = C\Delta T$.

Specific Heat and Latent Heat

Latent Heat

- **Latent Heat, Q_L :** The heat required for the substance to produce a phase change at constant temperature and given by

$$Q_L = \pm mL$$

- Where L is the specific latent heat required to change the phase of 1 kg of a substance at constant temperature and m is the mass.
- Types of Latent Heat Transfer
 - 1 **Latent Heat of Fusion (L_f):** is the heat absorbed or released when matter melts, changing phase from solid to liquid form at constant temperature.
 - 2 **Latent Heat of Vaporization (L_v):** is the heat absorbed or released when matter vaporizes, changing phase from liquid to gas phase at constant temperature
- Example 1: How much heat energy is required to change a 40 g ice cube from a solid at -10^0 C to steam at 110^0 C? ($c_{ice} = 0.49 \text{ kcal/kg.k}$, $L_{f,ice} = 80 \text{ kcal/kg}$, $L_{v,water} = 540 \text{ kcal/kg}$, $c_{steam} = 0.48 \text{ kcal/kg.k}$)

Heat Transfer Mechanisms

Conduction

- Heat may be transferred from one place to another in different ways:
 - 1 conduction
 - 2 convection
 - 3 radiation
 - 4 direct burning
- **Conduction:** In this process, the transfer can be represented on an atomic scale as an exchange of kinetic energy between microscopic particles-molecules, atoms, and free electrons-in which less-energetic particles gain energy in collisions with more energetic particles.
- Metals are all good conductors of heat especially copper, aluminum and silver, because they have free electrons which are easily able to transfer heat energy. It is most obvious in solids, All liquids (except mercury) and gases are very poor conductors of heat.
- Conduction occurs when heat energy travels through a body, passing from particle to particle as they vibrate against each other.

Heat Transfer Mechanisms

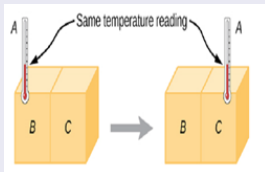
Convection, Radiation and Direct Burning

- **Convection:** is the transfer of heat by the movement of the heated particles themselves. This can only take place in liquids and gases because in solids the particles are not able to move from their fixed positions.
- **Radiation:** is the way we receive heat energy with help of electromagnetic wave like from the sun. It does not require a medium for its transmission (i.e. it can travel through empty space) and is in the form of electromagnetic energy waves which travel in the same way as light or radio waves.
- When these energy waves fall on a body, the energy may be absorbed, transmitted and reflected.
- Direct Burning: describe how physical contact of the flame with other available fuel spreads a fire.
- Exercise: Why Water is very effective as an extinguishing agent?

Law of Thermodynamics

Zeroth law of thermodynamics

- **Thermal contact:** two objects are in thermal contact with each other if energy can be exchanged between them due to a temperature difference.
- **Thermal equilibrium:** is a situation in which two objects would not exchange energy by heat or electromagnetic radiation if they were placed in thermal contact.
- **Zeroth law of thermodynamics** (the law of equilibrium): if object A is in thermal equilibrium with object B, and object B is in thermal equilibrium with object C, then object A is in thermal equilibrium with object C.



Law of Thermodynamics

The First Law for different thermodynamic systems

- **The first law of thermodynamics states that:** "The change in internal energy of a system is equal to the sum of the heat flow into the system and the work done on the system."
Mathematically , $\Delta U = Q + W$
- Where ΔU is the change in internal energy of the system, Q heat added on the system and W work done on the system.
- The first law is a specialized statement of energy conservation applied to a thermodynamic system, such as a gas inside a cylinder that has a movable piston.
- **Isolated system:** is a system which does not exchange heat with its surrounding and no work is done on the external environment. i.e. $Q = W = 0 \Rightarrow \Delta U = 0$.
- **Cyclic Process:** a process that starts and ends at the same state.
i.e. $\Delta U = 0 \Rightarrow Q = -W$

Law of Thermodynamics

The First Law for different thermodynamic systems

- **Isochoric process:** the volume of the system stays constant. i.e. $W = -P \Delta V = 0 \Rightarrow \Delta U = Q$
- **Adiabatic Process:** the system does not exchange heat with its surroundings. i.e. $Q = 0 \Rightarrow \Delta U = W$
- **Isothermal Process:** is a process which involves no change in the temperature of the system. i.e. $\Delta U = 0 \Rightarrow Q = -W$

Isothermal Expansion of an Ideal Gas

- Suppose that an ideal gas is allowed to expand quasi-statically at constant temperature.
- Let us calculate the work done on the gas in the expansion from state i to state f.
- Since we have the expression $PV = nRT$ for ideal gas, PV is constant with T is constant.

Law of Thermodynamics

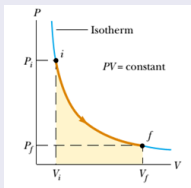
The First Law for different thermodynamic systems

- Work done on the ideal gas,

$$W = - \int_{V_i}^{V_f} P dV = - \int_{V_i}^{V_f} \frac{nRT}{V} dV$$

$$W = -nRT \int_{V_i}^{V_f} \frac{dV}{V}$$

$$W = nRT \ln\left(\frac{V_i}{V_f}\right)$$



- **Isobaric process:** the expansion or compression occurs at constant pressure. i.e. $W = -P(V_f - V_i) \Rightarrow \Delta U = Q - P(V_f - V_i)$
- Any work done by the system will result in an increase in volume.
- The work done in Pressure - Volume graph is equal to the area under the PV graph

Law of Thermodynamics

The First Law for different thermodynamic systems

- Example 1: A 1.0 mol sample of an ideal gas is kept at 0.0°C during the expansion from 3 L to 10 L.
 - ① How much work is done on the gas during the expansion?
 - ② How much energy transfer by the heat occurs with the surrounding in this process?
 - ③ if the gas is turned to the original volume by means of an isobaric process, how much work is done on the gas?
- Example 2: 5000 J of heat are added to two moles of an ideal monatomic gas, initially at a temperature of 500 K, while the gas performs 7500 J of work. What is the final temperature of the gas?

Entropy and the Second law of thermodynamics

- **Entropy** : a measure of the amount of disorder in a system
- **The second law of thermodynamics** states that: "No process is possible in which there is an overall decrease in the entropy of the universe."

Exercise

- ❶ A steel rod has a length of exactly 20 cm at 30°C . How much longer is it at 50°C ? ($\alpha_{\text{steel}} = 11 \times 10^{-6}/^{\circ}\text{C}$)
- ❷ By how much does the volume of an aluminum cube 5.00 cm on an edge increase when the cube is heated from 10.0°C to 60.0°C ? [Use $\alpha_{\text{Al}} = 23 \times 10^{-6}/^{\circ}\text{C}$]
- ❸ A 0.500 kg aluminum pan on a stove is used to heat 0.250 liters of water from 20.0°C to 80.0°C .
(a) How much heat is required? What percentage of the heat is used to raise the temperature of (b) the pan and (c) the water?
- ❹ If the amount of heat needed for a phase change is 300 kcal, calculate the latent heat of a 5 kg material.
- ❺ At 20°C , a piece of metal has a density of 60g. When immersed in a steam current at 100°C , 0.5g of the steam condenses on it. Provided that the latent heat of steam is 540 cal/g, calculate the specific heat of the metal.
- ❻ Describe the fundamental principles of heat engines and refrigerators.