Chapter 21

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Thermal Properties

Thermal Expansion

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- When a substance is heated, its volume usually increases, and each dimension increases correspondingly. This increase in size can be understood in terms of the increased kinetic energy of the atoms or molecules. The additional kinetic energy results in each molecule colliding more forcefully with its neighbors. The molecules effectively push each other farther apart, and the material expands.
- This phenomenon plays an important role in many engineering applications, such as the joints in buildings, highways, railroad tracks, bridges . . . etc. If the thermal expansion of an object is sufficiently small compared to its initial dimensions, then the change in any dimension (length, width, or thickness) is a linear function of the temperature.

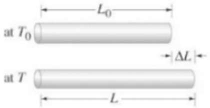
Thermal Expansion: Linear Expansion

- The change in length:

$$\Delta L = \alpha L_{\circ} \Delta T$$

- The new length:

$$L = L_{\circ}(1 + \alpha \Delta T\ )$$



Thermal Expansion: Linear Expansion

- Where:

$$\Delta L = L - L_{\circ}$$
$$\Delta T = T - T_{\circ}$$

  - $L_{\circ}$: the original length (m)
  - L: the new length (m)
  - ΔL: the change in length (m)
  - $T_{\circ}$: the initial temperature (℃) or (K)
  - T: the final temperature (℃) or (K)
  - ΔT: the change in temperature (℃) or (K)
  - α: the **coefficient of linear expansion.**
    - **represents the fractional change in length** $(\Delta L/L)$ **per one degree** change in temperature.
    - it has units of $(℃^{-1})$ or (K^{-1}).

Thermal Expansion: Area Expansion

- The change in area:

$$\Delta A = \gamma A_{\circ} \Delta T$$

- The new area:

$$A = A_{\circ}(1 + \gamma \Delta T\ )$$

For solids:

$$\gamma = 2\alpha$$

Thermal Expansion: Area Expansion

- Where:

$$\Delta A = A - A_{\circ}$$
$$\Delta T = T - T_{\circ}$$

  - $A_{\circ}$: the original area (m^2)
  - A: the new area (m^2)
  - ΔA: the change in area (m^2)
  - $T_{\circ}$: the initial temperature (℃) or (K)
  - T: the final temperature (℃) or (K)
  - ΔT: the change in temperature (℃) or (K)
  - γ: the **coefficient of area expansion.**
    - **represents the fractional change in area** $(\Delta A/A)$ **per one degree** change in temperature.
    - it has units of ($℃^{-1}$) or (K^{-1}).

Thermal Expansion: Volume Expansion

- The change in volume:

$$\Delta V = \beta V_\circ \Delta T$$

- The new volume:

$$V = V_\circ(1 + \beta \Delta T\ )$$

For solids:

$$\beta = 3\alpha$$

Thermal Expansion: Volume Expansion

- Where:

$$\Delta V = V - V_\circ$$
$$\Delta T = T - T_\circ$$

- $V_\circ$: the original volume (m^3)
- V: the new volume (m^3)
- ΔV: the change in volume (m^3)
- $T_\circ$: the initial temperature (℃) or (K)
- T: the final temperature (℃) or (K)
- ΔT: the change in temperature (℃) or (K)
- β: the **coefficient of volume expansion.**
  - **represents the fractional change in volume $(\Delta V/V)$ per one degree** change in temperature.
  - it has units of ($℃^{-1}$) or (K^{-1}).

Heat Capacity and Specific Heat

- When an object at one temperature is placed near or in contact with another object at a higher temperature, energy is transferred to the cooler object, and its temperature rises. The ratio of the amount of energy transferred to the temperature change is called the **heat capacity**.
- When energy transfer occurs because of temperature difference, we say that thermal energy or heat is being transferred. Alternatively, energy may be transferred by doing work on the substance.
- Suppose a small amount of heat, (ΔQ) , is transferred to (n) moles of a substance. We know from the first law of thermodynamics that the internal energy will increase or the substance will do work, or possibly both will happen. The **molar heat capacity** (C) is defined as:

$$C = \frac{1}{n}\frac{\Delta Q}{\Delta T}$$

- That is, (C) is the ratio of the heat added per mole to the rise in temperature. Substances which have a high molar heat capacity, experience relatively small temperature changes when a given amount of heat is transferred.

Heat Capacity and Specific Heat

- If heat is added with the volume of the substance kept constant, no work is done. Then the heat (ΔQ) added is equal to the internal energy change (ΔU), and the **molar heat capacity at constant volume** is:

$$C_v = \frac{1}{n}\frac{\Delta U}{\Delta T}$$

- For (n) moles or (nN_A) molecules of an **ideal monoatomic gas**, the internal energy (U) is the sum of the kinetic energies of the molecules, $\left(U = nN_A K_{avg} = \frac{3}{2}nRT\right)$. If the gas does not change its volume as the heat is added, and the temperature increases by (ΔT), the change in internal energy is $\left(\Delta U = \frac{3}{2}nR\Delta T\right)$. Hence the molar heat capacity at constant volume is:

$$C_v = \frac{1}{n}\frac{\Delta U}{\Delta T} = \frac{3}{2}R$$

Heat Capacity and Specific Heat

- If heat is added with the pressure is kept constant, the internal energy increases and some work is done; $(\Delta Q = \Delta U + W)$. Using the ideal gas law, $(PV = nRT)$, the work done at constant pressure when the temperature changes by (ΔT) is $(W = P\Delta V = nR\Delta T)$. Thus, $(\Delta Q = \Delta U + nR\Delta T)$, and the **molar heat capacity at constant pressure** is:

$$C_P = \frac{1}{n}\frac{\Delta Q}{\Delta T} = \frac{1}{n}\frac{\Delta U}{\Delta T} + R = C_v + R = \frac{5}{2}R$$

$$\rightarrow C_P = \frac{5}{2}R$$

Latent Heat and Phase Changes

- When heat energy is transferred from one substance to another, the temperature of the substance often changes. However, there are situations in which the transfer of energy does not change the temperature. Instead, the substance may change from one form to another. Such a change is commonly referred to a **phase change**.
- We consider the following two main common phase changes:
- 1. A phase change from solid to liquid (as ice melting) and from liquid to gas (as water boiling), where heat energy is absorbed while the temperature remains constant.
- 2. A phase change from gas to liquid (as steam condensing) and from liquid to solid (as water freezing), where heat energy is released while the temperature remains constant.
- The amount of heat energy per unit mass, L, that must be transferred when a substance completely undergoes a phase change *without changing temperature* is called the **latent heat.**

Latent Heat and Phase Changes

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- If a quantity Q of heat energy transfer is required to change the phase of a pure substance of a mass m, then $L = Q/m$ characterizes an important thermal property of that substance. That is:

$$Q = \mp mL$$

- A positive sign is used in this equation when energy enters the system, causing melting or vaporization of the substance, while a negative sign corresponds to energy leaving the system such that the substance condenses or solidifies.

Latent Heat and Phase Changes

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- When a substance experiences a phase change from solid to liquid by absorbing heat, the heat of transformation is called the **latent heat of fusion** L_f. When the substance releases heat and experiences a phase change from liquid back to solid, the heat of transformation is called the **latent heat of solidification** and is numerically equal to the latent heat of fusion. In the case of water at its normal melting or freezing temperature, we have:

$$L_f = 3.33 \times 10^5 \ J/kg$$

- When a substance experiences a phase change from liquid to gas by absorbing heat, the heat of transformation is called the **latent heat of vaporization** L_v, see. When the gas releases heat and experiences a phase change from gas back to liquid, the heat of transformation is called the **latent heat of condensation** and is numerically equal to the latent heat of vaporization. For water at its normal boiling and condensation temperatures, we have:

$$L_v = 2.256 \times 10^6 \ J/kg$$

Latent Heat and Phase Changes

- Phase changes can be described in terms of a rearrangement of molecules when heat energy is added or removed from a substance. Consider, for example, the solid-to-liquid phase change. The molecules in the solid are strongly attracted to each other. As thermal energy is absorbed, the molecules usually move further apart and their potential energy increases. This leads to no change in the average kinetic energy of the molecules during the melting process, which involves molecules moving from fixed lattice positions to a random liquid state, the temperature stays constant. The latent heat of fusion is equal to the work done in separating the molecules during the melting process and hence breaking their bonds and transforming the substance from the ordered solid phase into the disordered liquid phase.
- Now, we consider the liquid to gas phase change. The attractive forces between molecules in liquid form are stronger than in gas form because the average distance between molecules is smaller in the liquid state. As described in the solid-to-liquid phase transition, work must be done against these attractive forces. The latent heat of vaporization is the amount of energy added to the molecules in liquid form to accomplish this.