University Physics with Modern Physics - Modern Physics by Young and Freedman Notes

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17 Temperature and Heat

17.1 Temperature and Thermal Equilibrium

- The **zeroth law of thermodynamics** states: If C is initially in thermal equilibrium with both A and B, then A and B are also in thermal equilibrium with each other.
- Two systems are in thermal equilibrium iff they have the same temperature.

17.2 Thermometers and Temperature Scales

- Water freezes at 0°C or 32°F and boils at 100°C or 212°F.
- A temperature measurement is denoted x°C ("x degrees Celsius") whereas a temperature interval is denoted xC° ("x Celsius degrees").

17.3 Gas Thermometers and the Kelvin Scale

- Under the **Kelvin** temperature scale temperature differences are equal to those of the degrees Celsius scale, but the zero is equal to $-273.15°\text{C}$. This is known as **absolute zero** where molecules have their lowest possible kinetic and potential energies.
- The ratio of two temperatures in the Kelvin scale equals the ratio of the corresponding pressures in a constant-volume gas thermometer

$$\frac{T_2}{T_1} = \frac{p_2}{p_1}.$$

17.4 Thermal Expansion

- Materials expand when their temperatures increase.
- Expansion in a single dimension is described by the equation

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

  where ΔL is the change in length, α is the **coefficient of linear expansion**, L_0 is the original length, and ΔT is the change in temperature.
- Expansion in three dimensions (volume expansion) is described by the equation

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

  where ΔV is the change in volume, β is the **coefficient of volume expansion** (equal to 3α), V_0 is the original volume, and ΔT is the change in temperature.
- If the ends of a material are fixed in place, changes in temperature can induce **thermal stresses** that can damage the material. The magnitude of these stresses is given by

$$\frac{F}{A} = -Y\alpha\Delta T.$$

17.5 Quantity of Heat

- Energy transferred as a result of a temperature difference is called **heat**.
- The **specific heat** of a material is the amount of energy required to raise the temperature of one unit of mass of the material by one unit of temperature, e.g. 1 kg by 1 K. It has units like J/(kg K).
- The specific heat of water is

$$4190\,\text{J/(kg K)} \text{ or } 1\,\text{cal/(g C°)}.$$

- The energy required to change the temperature of a material is given by

$$Q = mc\Delta T$$

  where m is the mass of the material, c is its specific heat, and ΔT is the change in temperature.

- The **molar mass** of a substance is the mass of one mole.

- The total mass of a material m is equal to the mass per mole M times the number of moles n

$$m = nM.$$

- The energy required to change the temperature of a certain number of moles of a substance is

$$Q = nC\Delta T$$

  where $C = Mc$ is the **molar heat capacity**.

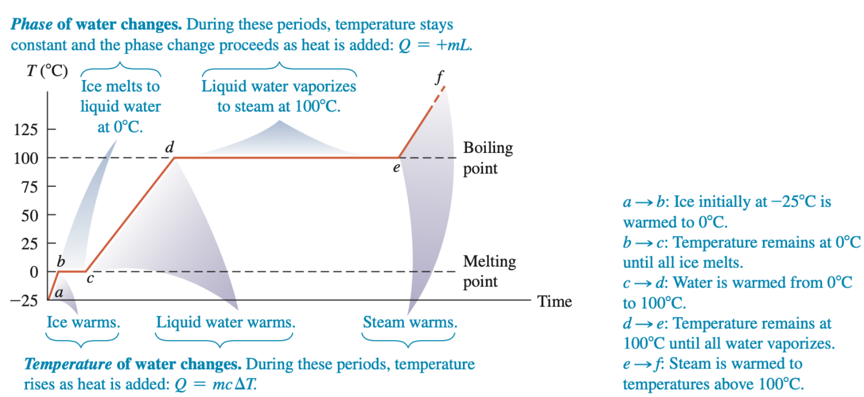
17.6 Calorimetry and Phase Changes

- A **phase** is a specific state of matter, e.g. solid, liquid, or gas.

- A **phase change** or **phase transition** is a transition from one phase to another.

- For a given pressure, phase change takes places at a definite temperature.

- While a substance is undergoing a phase change, any added or removed energy will affect the progress of the phase change but won't change the temperature.



- The heat transfer required for a material to undergo a phase change is given by

$$Q = \pm mL$$

where the $\pm$ indicates that heat may need to be added or removed depending on the direction of the phase change (e.g. energy must be added to melt ice), m is the mass of the material, and L is the latent heat associated with the phase change.

- When a material is freezing or melting, $L = L_f$ the **latent heat of fusion**.
- When a material is condensing or vaporising, $L = L_v$ the **latent heat of vaporisation**.
- When a material sublimates (changes directly from a solid to a gas, skipping liquid) or deposits/desublimates (changes directly from a gas to a solid, skipping liquid), $L = L_s$ the **latent heat of sublimation**.
- When a material burns, $L = L_c$ the **latent heat of combustion**.
- For any given material at any given pressure, the freezing temperature is the same as the melting temperature. This is called **phase equilibrium**. Similarly the condensing temperature is the same as the vaporisation temperature.

17.7 Mechanisms of Heat Transfer

- **Conduction** is a mechanism of heat transfer where the molecules in an area of high temperature have greater kinetic energy, they bump neighboring molecules which increases their kinetic energy, and so on spreading the heat through the material.
- The direction of heat flow is always from higher to lower temperature.
- When a quantity of heat dQ is transferred through a material in time dt we say the rate of heat flow or the **heat current** is

$$H = \frac{dQ}{dt}.$$

- If a rod has cross sectional area A, length L, one end is held at temperature T_H, and the other is held at T_C where $T_H > T_C$, the heat current is

$$H = \frac{dQ}{dT} = kA\frac{T_H - T_C}{L}$$

  where k is the **thermal conductivity** of the material and $(T_H - T_C)/L$ is the temperature difference per unit length or the magnitude of the **temperature gradient**.

- **Convection** is the transfer of heat by mass motion of fluid from one region of space to another, e.g. ducted cooling/heating. If the fluid is circulated by a blower or a pump the process is called **forced convection**; if the flow is caused by differences in density due to thermal expansion, such as hot air rising, the process is called **free convection**.

- **Radiation** is the transfer of heat by electromagnetic waves such as visible light, infrared, and ultraviolet radiation.

- The wavelength of the radiation depends on temperature. At 20 °C the radiation is infrared. At 800 °C the radiation is red. At 3000 °C the radiation is white.

- The **Stefan-Boltzmann law** gives the rate of energy radiation from a surface
$$H = Ae\sigma T^4$$
where A is its surface area, e is a dimensionless constant between 0 and 1 called the **emissivity** of the surface (1 would be a perfect radiator), σ is the **Stefan-Boltzmann constant**
$$\sigma = 5.670\,374\,42 \times 10^{-8}\,\mathrm{W/(m^2\,K^4)},$$
and T is the temperature in Kelvin.

- An object's surroundings also emit radiation which is absorbed by the object. The net heat current from the object is this
$$H = Ae\sigma(T^4 - T_s^4)$$
where T_s is the temperatue of the surroundings. At thermal equilibrium there is no heat flow.

- An object that is a good absorber must also be a good emitter. An ideal radiator with $e = 1$ is also an ideal absorber, absorbing all the raditation that hits it. Such a surface is called an **ideal black body** or a **blackbody**.