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

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Contents

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 $-273.15°$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. $1\,\text{kg}$ by $1\,\text{K}$. It has units like $\text{J}/(\text{kg}\,\text{K})$.

- The specific heat of water is

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

- 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
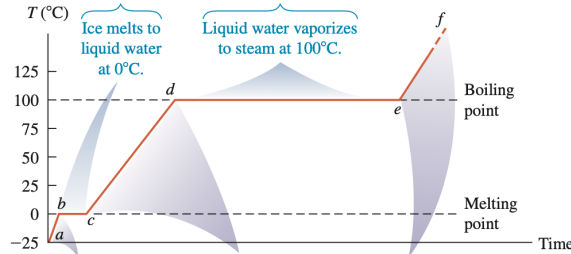$$Q = nC\Delta T$$

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.

T (°C)

Ice melts to
liquid water
at 0°C.

Liquid water vaporizes
to steam at 100°C.

f

125
100
75
50
25
0
−25

d

Boiling
point

e

b

c

a

Melting
point

Time

Ice warms.   Liquid water warms.   Steam warms.

Temperature of water changes. During these periods, temperature
rises as heat is added: $Q = mc\,\Delta T$.

$a \to b$: Ice initially at −25°C is
warmed to 0°C.
$b \to c$: Temperature remains at 0°C
until all ice melts.
$c \to d$: Water is warmed from 0°C
to 100°C.
$d \to e$: Temperature remains at
100°C until all water vaporizes.
$e \to f$: Steam is warmed to
temperatures above 100°C.

- 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 depend-
ing 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, skip-
  ping 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 tem-
  perature.

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 neigh-
  boring 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.

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- 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**.

18 Thermal Properties of Matter

18.1 Equations of State

- Quantities such as pressure, volume, temperature, and amount of substance are called **state variables**.

- An equation that relates state variables is called an **equation of state**.

- Molar mass (i.e. the mass of one mole of a substance) is sometimes called **molecular weight**.

- The **ideal gas equation** relates the absolute pressure p, volume V, number of moles n, and absolute temperature (in Kelvin) T

$$pV = nRT$$

or

$$pV = \frac{m_{\text{total}}}{M} RT$$

where R is the gas constant

$$R = 8.314 \, \text{J}/(\text{mol K}).$$

- If the amount of a gas is contant, i.e. nR is constant, then

$$\frac{p_1 V_1}{T_1} = \frac{p_2 V_2}{T_2} = \text{constant}.$$

- **Standard temperature and pressure** (STP) is defined as $0\,^\circ\text{C}$ and $1\,\text{atm}$.

- The **van der Waals** equation extends the ideal gas law to account for the effects of interactions between gas molecules and their finite size

$$\left(p + \frac{an^2}{V^2} \right)(V - nb) = nrT$$

where a and b are constants that vary between gases, a depends on the strength of attractive forces between the molecules, and b depends on the volume of the molecules.

- A pV-diagram is a two-dimensional diagram plotting pressure as a function of volume. Each line, called an **isotherm**, describes the relationship between pressure and volume at a particular temperature.

- In the pV-diagrams of non-ideal gases, isotherms can have flat areas. These represent periods where the gas is condensing into a liquid.

- The area under a pV-curve represents the work done by the system during a volume change.

18.2 Molecular Properties of Matter

- The force between molecules in a gas varies with r.

- An ideal gas is one whose molecules exert no attractive forces on each other and thus have no potential energy.

- The number of molecules in a mole is given by **Avagadro's number**

$$N_A = 6.022\,140\,76 \times 10^{23} \text{ molecules/mol.}$$

18.3 Kinetic-Molecular Model of an Ideal Gas

- The average translational kinetic energy of an ideal gas is

$$K_{\text{tr}} = \frac{3}{2}nRT.$$

- The **Boltzmann constant** is

$$k = \frac{R}{N_A} = 1.381 \times 10^{-23} \text{ J/(molecule K).}$$

- The average translational kinetic energy of a gas molecule is

$$\frac{1}{2}m(v^2)_{\text{av}} = \frac{3}{2}kT$$

and thus the **root-mean-square speed** of a gas molecule is

$$v_{\text{rms}} = \sqrt{(v^2)_{\text{av}}} = \sqrt{\frac{3kT}{m}} = \sqrt{\frac{3RT}{M}}$$

where m is the mass of a molecule and M is the molar mass.

- The average distance travelled by a particle between collisions is called the **mean free path**

$$\lambda = \frac{V}{4\pi\sqrt{2}r^2 N} = \frac{kT}{4\pi\sqrt{2}r^2 p}$$

where V is the volume of the gas, r is the radius of a gas molecule, N is the number of molecules in the gas, T is its temperature, and p is its volume.

18.4 Heat Capacities

- The **molar heat capacity at constant volume** of a particular gas is determined by its **degrees of freedom**, i.e. the number of ways in which it can store kinetic energy.

- Monatomic gases have three degrees of freedom: one for each translational axis.

- Diatomic gases have five degrees of freedom: one for each translational axis and two for rotational axes (the third is excluded because it's not affected by collisions).

- Polyatomic gases have more than five degrees.

- The **principle of equipartition of energy** states that each degree of freedom contributes $\frac{1}{2}kT$ to the molar heat capacity at constant volume, i.e. for monatomic gases $C_V = \frac{3}{2}kT$, for diatomic $C_V = \frac{5}{2}kT$, etc.

- Vibrational energy can also contribute to the molar heat capacity at constant volume, but for most diatomic molecules this isn't the case.

- Molar heat capacity at constant volume is temperature dependent, with rotational and vibrational degrees of freedom only coming in to play at higher temperatures.

- Crystalline solids, i.e. solids whose atoms are arranged in a three-dimensional matrix, have six degrees of freedom: three translational and three from the potential energy of intermolecular forces. This results in the **rule of Dulong and Petit** which states that the molar heat capacity at constant volume of an ideal monatomic solid is

$$V_C = 3R.$$

18.5 Molecular Speeds

- In regards to the speeds of molecules in a gas, a **distribution function** $f(v)$ gives the probability per unit speed of finding a particle with a speed near v. That is, the area under the curve between $f(v_1)$ and $f(v_2)$ gives the probability of finding a particle with speed in that range.

- The **Maxwell-Boltzmann distribution** is a particular distribution function

$$f(v) = 4\pi \left(\frac{m}{2\pi kT} \right)^{3/2} v^2 e^{-mv^2/2kT}$$

where m is the mass of a molecule, T is the absolute temperature of the gas, and v is the molecular speed.

- The peak of the curve and thus the most probable speed occurs at

$$v_{\text{mp}} = \sqrt{\frac{2kT}{m}}.$$

- The average speed is

$$v_{\text{av}} = \sqrt{\frac{8kT}{\pi m}}.$$

- The rms speed is

$$v_{\text{rms}} = \sqrt{\frac{3kT}{m}}.$$

18.6 Phases of Matter

- A pT **phase diagram** is a two-dimensional graph with pressure p on the vertical axis and temperature T on the horizontal axis. The plane is separated into three distinct regions: one for each phase of the material (solid, liquid, and gas).

- The borders between regions represent points of **phase equilibrium** where both phases can coexist at the same pressure and temperature.

- The **fusion curve** separates the solid and liquid regions.

- The **vaporisation curve** separates the liquid and gas regions.

- The **sublimation curve** separates the solid and gas regions.

- The three curves meet at the **triple point** — the only conditions under which all three phases can coexist.

- The vaporisation curve ends at the **critical point**. As the pressure and temperature of a substance approaches those of its critical point the physical differences between the liquid and gas phases decrease. At the critical point there are no differences and a substance whose pressure or temperature is gradually decreased won't undergo a phase transition — instead its properties will continuously change from those of a gas to those of a liquid or vice versa.