Thermal Physics

A Level Physics 9702

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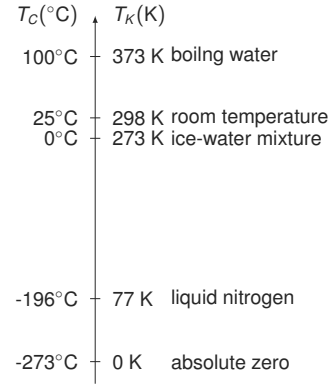
By the end of this topic I can...

- use the Celsius and Kelvin scales; describe solids, liquids and gases with the kinetic model
- use specific latent heat and specific heat capacity
- define internal energy and explain how it changes
- use the first law $\Delta U = Q + W$ and $W = p\Delta V$
- describe thermal equilibrium, absolute zero and thermometers

Temperature scales

- **Celsius**: 0 ℃ ice–water mixture, 100 ℃ boiling water
- **Kelvin**: 0 K is **absolute zero**
- a change of 1 ℃ = a change of 1 K

$$T_K\,(\mathrm{K}) \underset{+273.15}{\overset{-273.15}{\rightleftharpoons}} T_C\,(^\circ\mathrm{C})$$



Kinetic theory of matter

- **solid**: close, tightly bonded, vibrate about fixed positions
- **liquid**: quite close, vibrate and move about
- **gas**: widely separated, free, rapid motion
- microscopic behaviour explains macroscopic properties

Specific latent heat

Specific latent heat L

Thermal energy to change the **state** of **unit mass** with **no change in temperature**.

- unit: J kg^{-1}
- fusion (melting) and vaporisation (boiling); $L_{vap} > L_{fus}$

$$Q = Lm$$

Example: boiling a kettle dry

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$$Q = mL = 0.50 \times 2.26 \times 10^6 = 1.13 \times 10^6 \text{ J}$$
$$t = \frac{Q}{P} = \frac{1.13 \times 10^6}{3.0 \times 10^3} \approx 380 \text{ s} \approx 6.3 \text{ min}$$

Example: latent heat of ice

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Heat also enters from the surroundings: $mL = (P_{\text{heater}} + P_{\text{sur}})\, t$

$$40.4\, L = (60 + P_{\text{sur}}) \times 180$$
$$56.6\, L = (90 + P_{\text{sur}}) \times 180$$

Subtracting: $16.2\, L = 30 \times 180 \quad \Rightarrow \quad L \approx 333\ \text{J g}^{-1}$, and $P_{\text{sur}} \approx 14.8\ \text{W}$.

Specific heat capacity

Specific heat capacity c

Thermal energy **per unit mass** to raise the temperature by **one unit**.

- unit: J kg^{-1} K^{-1}

$$Q = cm\Delta T$$

Example: ice in water

Example: ice in water

Energy lost by hot water = energy gained by ice (warm to 0 °C, melt, warm to T):

$$4200 \times 0.27 \times (80 - T) = 2100 \times 0.030 \times 20 + 3.3 \times 10^5 \times 0.030 + 4200 \times 0.030 \times T$$

$$90\,720 - 1134\,T = 1260 + 9900 + 126\,T$$

$$T = \frac{90\,720 - 1260 - 9900}{1134 + 126} \approx 63\,^\circ\text{C}$$

Example: aluminium block

A 1.00 kg aluminium block is heated by a heater with current 4.2 A and p.d. 12 V. The graph shows the temperature rising. Find the specific heat capacity of aluminium.

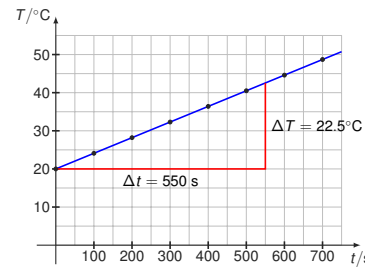
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$$IV\Delta t = cm\Delta T \quad \Rightarrow \quad c = \frac{IV}{m\Delta T/\Delta t}$$

gradient of the line: $\dfrac{\Delta T}{\Delta t} = \dfrac{22.5}{550} \approx 4.09 \times 10^{-2}\ ^\circ\text{C s}^{-1}$

$$c = \frac{4.2 \times 12}{1.00 \times 4.09 \times 10^{-2}} \approx 1230\ \text{J kg}^{-1}\ ^\circ\text{C}^{-1}$$



Internal energy

Internal energy

The sum of the **random kinetic energy** of molecules and the **potential energy between** them.

- state function: depends only on the current state
- mean K.E. $\propto T$; P.E. rises with separation and bond breaking

$$U = E_k + E_p$$

Internal energy of an ideal gas

Ideal gas

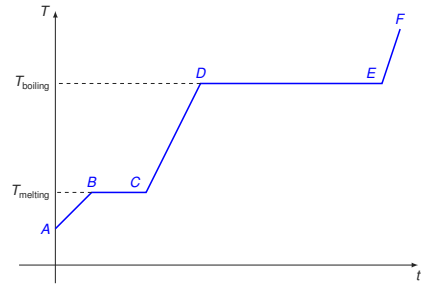
No intermolecular forces, so $E_p = 0$: the internal energy is purely **kinetic**.

- directly proportional to temperature

$$U = \frac{3}{2}NkT$$

Heating curve

- *AB*: E_k up, E_p constant
- *BC* melting: E_k constant, E_p **up**
- *CD*: E_k up, E_p constant
- *DE* boiling: E_k constant, E_p **up**
- *EF*: E_k up, $E_p = 0$



Evaporation vs boiling

- evaporation: at the **surface**, at **any temperature**, no bubbles, slow
- boiling: **throughout**, at the boiling point, bubbles, fast
- evaporation **cools**: the most energetic molecules escape
- faster at higher temperature and larger surface area

First law of thermodynamics

First law

The **increase in internal energy** = **heat supplied to** the system + **work done on** it.

- $Q > 0$ heat in; $W > 0$ compression, $W < 0$ expansion

$$\Delta U = Q + W$$

$$W = p\,\Delta V$$

Example: expanding gas

Example: expanding gas

Work: $|W| = p\Delta V = 150 \times 0.10 = 15$ kJ; the gas expands, so $W = -15$ kJ.
$\Delta U = Q + W = (+25) + (-15) = +10$ kJ

Example: why boiling needs heat

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Boiling is at constant temperature, so $\Delta E_k = 0$; the molecules separate, so $\Delta E_p > 0$.
Hence $\Delta U > 0$.
The volume increases, so work is done against the surroundings: $W < 0$.
$\Delta U = Q + W$ with $\Delta U > 0$ and $W < 0$ requires $Q > 0$: heat must be supplied.

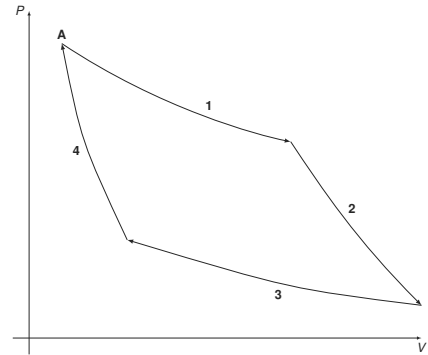
Example: pumping a tyre

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Compressing the gas: $W > 0$. Each stroke is quick, so little heat transfer: $Q \approx 0$.
$\Delta U = Q + W > 0$. For a gas $\Delta E_p = 0$, so $\Delta E_k > 0$.
Mean K.E. is proportional to temperature, so the temperature rises.

Carnot cycle

- 1 isothermal expansion: absorbs heat
- 2 adiabatic expansion: T falls
- 3 isothermal compression: loses heat
- 4 adiabatic compression: T rises
- over the cycle $\Delta U = 0$

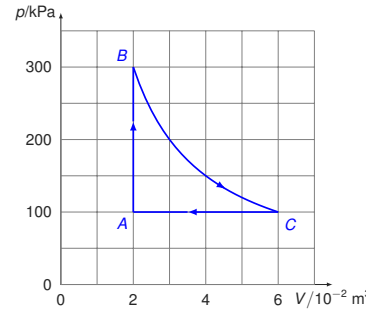


Example: the cycle ABCA

0.80 mol of an ideal gas goes round the cycle *ABCA* shown. $T_A = 300$ K and the magnitude of the work from B to C is 6570 J. For each stage find W, Q and ΔU.

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Work: $A \to B$: no volume change, $W = 0$. $B \to C$: expansion, $W = -6570$ J. $C \to A$: compression at 100 kPa, $W = +1 \times 10^5 \times 4 \times 10^{-2} = +4000$ J.
ΔU (ideal gas, $\frac{3}{2}Nk\Delta T$): $A \to B$: same V, p triples so $T_B = 900$ K and
$\Delta U = \frac{3}{2}nR\Delta T = \frac{3}{2} \times 0.80 \times 8.31 \times 600 \approx +5980$ J.
$B \to C$: pV unchanged so $\Delta T = 0$, $\Delta U = 0$. $C \to A$: $\Delta U = -5980$ J.
First law $Q = \Delta U - W$: $Q_{AB} = +5980$ J,
$Q_{BC} = +6570$ J, $Q_{CA} = -5980 - 4000 = -9980$ J.

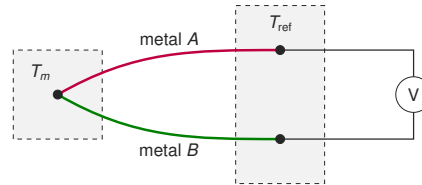
Thermal equilibrium and absolute zero

- heat flows from hot to cold; equal temperatures: **no net transfer**
- **zeroth law**: A and B each in equilibrium with C, so in equilibrium with each other
- **absolute zero**: minimum molecular K.E.; Kelvin scale is an absolute scale

$$T_K\,(\mathrm{K}) \underset{+273.15}{\overset{-273.15}{\rightleftharpoons}} T_C\,(^\circ\mathrm{C})$$

Thermometers

- **liquid-in-glass**: liquid expands
- **RTD** / **thermistor**: resistance changes with temperature
- **thermocouple**: thermoelectric voltage between junctions
- compare **range, sensitivity, response time, linearity**



Key equations

latent heat	$Q = Lm$	ideal gas	$U = \frac{3}{2}NkT$
heat capacity	$Q = cm\Delta T$	first law	$\Delta U = Q + W$
internal energy	$U = E_k + E_p$	work	$W = p\,\Delta V$