The particulate nature of matter

IB Diploma Physics

> *The data booklet is on the desk in every paper, so the useful question is what you have to supply yourself: the definitions, the decay bookkeeping, and the results you are expected to derive. Compiled by GioPhysics from the published syllabus. This is an independent study aid, not an IB document; the official syllabus is the authority.*

B.1 Thermal energy transfers

SL

Kelvin and Celsius

$$T / K = \theta / °C + 273$$

$\theta / °C = T / K - 273$

T — absolute temperature (K)
θ — temperature (°C)

Absolute zero is 0 K. Every gas and radiation equation below needs the temperature in kelvin.

SL

Specific heat capacity

$$Q = mc\Delta T$$

$c = Q / (m\Delta T)$ · $\Delta T = Q / (mc)$

Q — energy transferred (J)
m — mass (kg)
c — specific heat capacity (J kg^{-1} K^{-1})
ΔT — temperature change (K)

A temperature change in kelvin and in degrees Celsius is the same number, so either unit works here.

SL

Specific latent heat

$$Q = mL$$

Q — energy transferred (J)
m — mass changing phase (kg)
L — specific latent heat of fusion or vaporisation (J kg^{-1})

The temperature does not change during a phase change: the energy goes into potential energy between the molecules, not kinetic.

SL

Conduction

$$\frac{\Delta Q}{\Delta t} = kA\frac{\Delta T}{\Delta x}$$

ΔQ/Δt — rate of thermal energy transfer (W)
k — thermal conductivity (W m^{-1} K^{-1})
A — cross-sectional area (m^2)
ΔT/Δx — temperature gradient (K m^{-1})

Convection is treated qualitatively, through density differences in a fluid.

SL

Stefan–Boltzmann law

$$L = \sigma AT^4$$

L — power radiated by a black body (W)
σ — Stefan–Boltzmann constant (W m^{-2} K^{-4})
A — surface area (m^2)
T — surface temperature (K)

The fourth power is the point: doubling the absolute temperature multiplies the power by sixteen.

SL

Emissivity

e = power radiated by the body / power radiated by a black body of the same area and temperature

e — emissivity, between 0 and 1 (a ratio, no unit)

A black body has e = 1, so a real surface radiates $P = e\sigma AT^4$.

SL

Wien's displacement law

$$\lambda_{max} = 2.90 \times 10^{-3} / T$$

λmax — wavelength at which the emitted power peaks (m)
T — surface temperature (K)

The constant is in m K. Hotter bodies peak at shorter wavelengths, which is how a star's colour gives its temperature.

SL

Apparent brightness

$$b = L / (4\pi d^2)$$

b — apparent brightness, the intensity received ($W\ m^{-2}$)
L — luminosity, the power emitted (W)
d — distance to the source (m)

An inverse square law, because the power spreads over a sphere of area $4\pi d^2$. E.5 uses the same equation for stars.

B.2 Greenhouse effect

SL

Albedo

α = total scattered power / total incident power

α — albedo, between 0 and 1 (a ratio, no unit)

The fraction of incoming radiation reflected away. Ice and cloud raise it; open ocean and forest lower it.

SL

Solar intensity at a planet

$$S = L / (4\pi d^2)$$

S — intensity arriving on a surface facing the Sun ($W\ m^{-2}$)
L — luminosity of the Sun (W)
d — distance from the Sun (m)

At the Earth's orbit this is the solar constant, about $1.36 \times 10^3\ W\ m^{-2}$.

SL
DERIVED

Average intensity absorbed by a planet

average absorbed intensity = S(1 − α) / 4

S — solar intensity at that orbit ($W\ m^{-2}$)
α — albedo

Not printed in the data booklet. The factor of four is the disc the planet presents, πr^2, spread over the whole surface it radiates from, $4\pi r^2$.

SL

Power radiated by a planet

$$P = e\sigma AT^4$$

P — power radiated (W)
e — emissivity
σ — Stefan–Boltzmann constant ($W\ m^{-2}\ K^{-4}$)
A — surface area (m^2)
T — average surface temperature (K)

SL

Energy balance of a planet

power absorbed = power radiated

T — the equilibrium temperature this fixes (K)

Not printed in the data booklet. Greenhouse gases — CO_2, H_2O, CH_4, N_2O — absorb outgoing infrared and re-emit it, so equilibrium is reached at a higher surface temperature.

B.3 Gas laws

SL

Amount of substance

$$n = N / N_A$$

- n — amount of substance (mol)
- N — number of molecules
- N_A — Avogadro constant (mol^{-1})

SL

Ideal gas equation, by moles

$$pV = nRT$$

- p — pressure (Pa)
- V — volume (m^3)
- n — amount of substance (mol)
- R — molar gas constant ($J\ K^{-1}\ mol^{-1}$)
- T — absolute temperature (K)

SL

Ideal gas equation, by molecules

$$pV = NkBT$$

- N — number of molecules
- k_B — Boltzmann constant ($J\ K^{-1}$)
- T — absolute temperature (K)

The same statement counted in molecules rather than moles; $k_B = R / N_A$.

SL
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A fixed mass of gas, changing state

$$p_1V_1 / T_1 = p_2V_2 / T_2$$

- p, V, T — pressure, volume and absolute temperature before and after (Pa, m^3, K)

Not printed in the data booklet: it is $pV = nRT$ with n fixed. Hold one quantity constant and it becomes Boyle's, Charles's or Gay-Lussac's law.

SL

Average kinetic energy of a molecule

$$\bar{E}k = (3/2)kBT$$

- $\bar{E}k$ — average translational kinetic energy of one molecule (J)
- k_B — Boltzmann constant ($J\ K^{-1}$)
- T — absolute temperature (K)

This is what absolute temperature measures — and why 0 K is the floor.

SL

Internal energy of an ideal monatomic gas

$$U = (3/2)nRT = (3/2)NkBT = (3/2)pV$$

- U — internal energy (J)
- n — amount of substance (mol)
- T — absolute temperature (K)

N times the average molecular kinetic energy. An ideal gas has no intermolecular potential energy, so this is all of it. B.4 puts it into the first law.

SL
DERIVED

Root-mean-square speed

$$v_{rms} = \sqrt{(3kBT / m)} = \sqrt{(3RT / M)}$$

- v_{rms} — root-mean-square molecular speed ($m\ s^{-1}$)
- m — mass of one molecule (kg)
- M — molar mass ($kg\ mol^{-1}$)

Not printed in the data booklet: it is $\bar{E}k = \frac{1}{2}m\ v_{rms}^2$ set equal to $(3/2)kBT$. Lighter molecules move faster at the same temperature.

B.4 Thermodynamics

HL

First law of thermodynamics

$$Q = \Delta U + W$$

- Q — energy transferred to the gas by heating (J)
- ΔU — increase in internal energy (J)
- W — work done BY the gas (J)

Higher level only. Note the sign convention: W here is work done by the gas, so an expansion makes it positive.

HL

Work done by an expanding gas

$$W = p\Delta V$$

- W — work done by the gas (J)
- p — pressure (Pa)
- ΔV — change in volume (m^3)

Higher level only. At constant pressure. In general the work is the area under the p–V curve.

HL

Change in internal energy of a monatomic ideal gas

$$\Delta U = (3/2)nR\Delta T$$

- ΔU — change in internal energy (J)
- n — amount of substance (mol)
- ΔT — change in absolute temperature (K)

Higher level only. No temperature change means no change in internal energy, which is what makes an isothermal process tractable.

HL

Isothermal process

$$pV = \text{constant} \cdot W = nRT \ln(V_2 / V_1)$$

- W — work done by the gas (J)
- V_1, V_2 — initial and final volume (m^3)
- T — the constant absolute temperature (K)

Higher level only. $\Delta U = 0$, so $Q = W$: everything supplied by heating leaves as work.

HL

Adiabatic process for a monatomic ideal gas

$$pV^{(5/3)} = \text{constant}$$

- p — pressure (Pa)
- V — volume (m^3)

Higher level only. $Q = 0$, so $\Delta U = -W$: the gas cools as it expands because the work comes out of its internal energy.

HL

Entropy change

$$\Delta S = \Delta Q / T$$

- ΔS — change in entropy ($J\ K^{-1}$)
- ΔQ — energy transferred by heating (J)
- T — absolute temperature at which it is transferred (K)

Higher level only. The second law: the entropy of an isolated system never decreases.

HL

Efficiency of a heat engine

$$\eta = W / Qin = 1 - Qout / Qin$$

- η — efficiency (a ratio, no unit)
- W — useful work per cycle (J)
- Qin, Qout — energy taken from the hot reservoir and dumped to the cold one (J)

Higher level only.

HL

Carnot efficiency

$$\eta_{Carnot} = 1 - \frac{T_{cold}}{T_{hot}}$$

ηCarnot — the highest efficiency any engine between the two reservoirs can reach
Tcold, Thot — absolute temperatures of the two reservoirs (K)

Higher level only. A ceiling set by the temperatures alone — no engineering gets past it.

B.5 Current and circuits

SL

Electric current

$$I = \frac{\Delta q}{\Delta t}$$

$\Delta q = I\Delta t$

I — current (A)
Δq — charge passing a point (C)
Δt — time taken (s)

Conventional current runs from positive to negative; electrons drift the other way.

SL

Potential difference

$$V = \frac{W}{q}$$

V — potential difference (V)
W — work done on or by the charge (J)
q — charge moved (C)

SL

Resistance

$$R = \frac{V}{I}$$

$V = IR \quad \cdot \quad I = V / R$

R — resistance (Ω)
V — potential difference (V)
I — current (A)

This defines resistance for any component. It is Ohm's law only where R stays constant, which a filament lamp does not.

SL

Resistivity

$$R = \frac{\rho L}{A}$$

ρ — resistivity (Ω m)
L — length (m)
A — cross-sectional area (m²)

SL

Current and drift speed

$$I = nAvq$$

n — number density of charge carriers (m^{-3})
A — cross-sectional area (m^2)
v — drift speed ($m\ s^{-1}$)
q — charge on each carrier (C)

SL

Electrical power

$$P = IV = I^2R = \frac{V^2}{R}$$

P — power dissipated (W)
I — current (A)
V — potential difference (V)
R — resistance (Ω)

Pick the form that matches what is held constant — I^2R for a fixed current, V^2/R for a fixed supply.

SL

Resistors in series

$$R_s = R_1 + R_2 + \dots$$

R_s — combined resistance (Ω)

SL

Resistors in parallel

$$\frac{1}{R_p} = \frac{1}{R_1} + \frac{1}{R_2} + \dots$$

R_p — combined resistance (Ω)

The combined resistance is always smaller than the smallest branch.

SL

Kirchhoff's circuit laws

$$\Sigma I = 0 \text{ at a junction} \cdot \Sigma V = 0 \text{ around a loop}$$

I — currents in and out of the junction, with sign (A)
V — e.m.f.s and potential drops around the loop, with sign (V)

Not printed in the data booklet as equations. The first is conservation of charge, the second conservation of energy.

SL

e.m.f. and internal resistance

$$\varepsilon = I(R + r)$$

$V = \varepsilon - Ir$

ε — electromotive force of the cell (V)
I — current drawn (A)
R — external resistance (Ω)
r — internal resistance of the cell (Ω)

The terminal p.d. V is what a voltmeter across the cell reads, and it falls below ε as soon as current flows.