Unit 12 · Rate of Heat Flow

STUDY NOTES

WHAT NEB'S GRADE 11 EXAM ASKS

- **CDC's grid (2077):** Heat and Thermodynamics (Units 9–13 together): 15 of 75 marks
- **The paper:** 11 MCQs × 1 · 8 short × 5 · 3 long × 8; 3 hours; 1 mark per expected point
- **CDC's model paper:** a 5-mark short question from this unit: define temperature gradient (1), heat through an oven's fiberglass wall (3), effect of moisture (1)
- **MCQ (1 mark)**
  - convection needs gravity
  - what k depends on; its meaning
  - $E \propto T^4$; doubled $T \rightarrow 16\times$
  - good absorber = good emitter
  - no radiation only at 0 K
  - hotter above a fire
  - solid vs hollow sphere cooling
  - flow ratio from d and l
  - temperature along a rod; two layers
  - which color cools first
- **Short (5 marks, in parts)**
  - clouds on a winter night; blackened vs silvered bulbs; candle side vs top
  - metal vs wooden chair; nail in a potato; new quilt; pot's bottom temperature
  - thermos flask; double-walled ice houses; window loss; squirrel's tail
  - Earth not as hot as the Sun; body radiating in a warmer room; sun vs shade; heater's temperature
  - glasshouse; aluminium paint on tanks; Stefan's constant from a cooling sphere
  - copper-bottomed pans; a good cooking pot; k from melted ice
  - net radiation; the Sun's temperature from the solar constant

Key terms

Conduction: heat passed by vibrations and collisions of particles (and free electrons in metals), particles staying in place; needs a medium.

Convection: heat carried by the movement of the fluid itself; fluids only.

Radiation: heat sent as electromagnetic waves; no medium needed.

Temperature gradient: rate of change of temperature with distance, $d\theta/dx$; K/m.

Steady state: every point's temperature constant; each section passes on all the heat it receives.

Thermal conductivity k: rate of heat flow per unit area in the steady state when the temperature gradient is 1 unit.

Reflectance, absorptance, transmittance: $r = R/Q$, $a = A/Q$, $t = T/Q$.

Perfectly black body: absorbs all radiation falling on it, every wavelength ($a = 1$); also the best emitter.

Emissive power E: energy radiated per unit time per unit area; W/m^2.

Emissivity e: E of a body ÷ E of a black body at the same temperature; no unit; 0 to 1.

Stefan's law: emissive power of a perfectly black body $\propto$ fourth power of its absolute temperature.

Solar constant S: Sun's energy per second per m^2 at right angles to the rays, at Earth's mean distance, outside the atmosphere: 1361 W/m^2 ($\approx$ 1400).

Formulas

$\frac{Q}{t} = kA\,\frac{\theta_1 - \theta_2}{x}$	A area, x thickness; difference same in K or °C **Use:** conduction through a slab
$k = \frac{ms(\theta_3 - \theta_4)x}{At(\theta_1 - \theta_2)}$	m water in time t; θ_3 out, θ_4 in **Use:** Searle's method
$\frac{Q}{t} = hA\,\Delta\theta$	h convection coefficient, W/(m^2 K) **Use:** convection
$r + a + t = 1$	opaque: $r + a = 1$ **Use:** radiation falling on a body
$E = \sigma T^4$	$\sigma = 5.67 \times 10^{-8}$ W/(m^2 K^4); T **in K** **Use:** black body
$P = eA\sigma T^4$	e emissivity, A area **Use:** power radiated
$P' = eA\sigma(T^4 - T_0^4)$	T_0 surroundings (K) **Use:** net loss
$T = \left[\frac{S}{\sigma}\left(\frac{r}{R}\right)^2\right]^{1/4}$	r Sun–Earth, R Sun's radius **Use:** Sun's temperature $\approx$ 5800 K

- k: W/(m K); dimensions $[\mathrm{MLT^{-3}K^{-1}}]$
- lagged rod, steady state: uniform gradient $(\theta_1 - \theta_2)/l$; temperature falls in a straight line
- two layers: **same heat per second through each**; $k_1\Delta\theta_1/x_1 = k_2\Delta\theta_2/x_2$

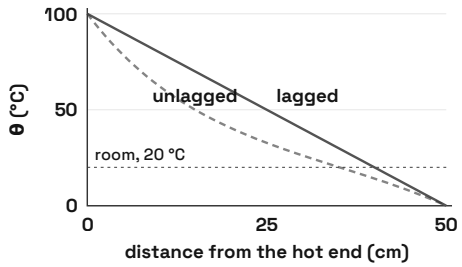
Conduction

- atoms vibrate harder, jostle neighbors; metals also by **free electrons** $\rightarrow$ good conductors of electricity conduct heat well
- **still air**: very poor conductor ($\approx$ 15 000 × poorer than copper); trapped air insulates
  - two thin jackets warmer than one thick
  - double walls, ice houses, double glazing, cold stores

- woolen clothes; ice in sawdust
- **new quilt** warmer: fluffy cotton holds more air

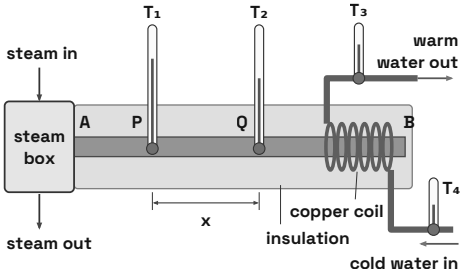
- warm a tight glass stopper's neck: glass expands before the stopper; metal pans, wooden or Bakelite handles
- **iron chair feels colder** than wood at the same temperature: carries heat from skin fast
- nail through a potato carries heat to its middle; aluminium (237) better than steel (≈ 50)

Material	k W/(m K)	Material	k W/(m K)
silver	429	glass	≈ 1
copper	401	water	0.6
aluminium	237	wood	0.1–0.2
iron	80	cork, wool	≈ 0.04
steel	≈ 50	still air	0.026



Lagged rod: straight-line fall, uniform gradient. Unlagged: steep near the hot end, then gentler (heat lost from the sides).

Searle's method



Thick, lagged copper bar: steam box at A, water coil at B (in θ_4, out θ_3); thermometers in mercury holes P, Q (θ_1, θ_2) a distance x apart.

- wait for **steady** readings (an hour or more); collect water for time t: mass m
- heat through bar $kA(\theta_1 - \theta_2)/x$ = heat to water $ms(\theta_3 - \theta_4)/t$
- **thick** bar: enough heat; **long**: several degrees between P and Q; **lagged**: uniform gradient; **mercury**: good contact; poor conductor: thin wide disc instead (Lee's disc)

Convection

- warm fluid expands, less dense → pushed up; cooler sinks; heat from **below**
- **natural**: gravity's upthrust (no convection in orbit: candle flame a dim ball); **forced**: pump, fan (heart, computer fan, car radiator, hair dryer)
- h: still air 5–25 W/(m^2 K); fan, wind, flowing water more → wind-chill
- hotter **above** a fire than beside it: hot gases rise by convection; beside it only radiation
- in nature
  - trade winds
  - sea, land breezes
  - ocean currents
  - ventilators, chimneys
  - monsoon (⅘ of Nepal's rain)

Radiation

- every body above 0 K radiates; at 0 K none
- through vacuum at 3×10^8 m/s; doesn't heat the medium; straight lines; reflected, refracted, interferes, diffracts, polarized
- mostly infrared at everyday temperatures; glows dull red ≈ 500 °C
- good absorber = poor reflector = **good emitter** (Kirchhoff, $e = a$); black cools first, white last
- black body: lamp black, platinum black (96–98%); **cavity with a small hole** (Féry's)
- e: perfect reflector 0; polished aluminium ≈ 0.05; brick ≈ 0.9; skin ≈ 0.97; black body 1
- T doubled → $E \times 16$; 27 °C = 300 K, 54 °C = 327 K (not 600 K)
- body at 25 °C in a room at 35 °C: still radiates, but absorbs more → net gain

Daily life

- heater's polished reflector; white clothes in summer, dark in winter
- blackened thermometer bulb: reads higher in sun, lower on a clear night; silvered the opposite
- clouds on a winter night send infrared back → warmer
- sun vs shade: air nearly the same; body absorbs the Sun's radiation directly
- glasshouse: light in; infrared from soil hardly passes glass; warm air can't rise away
- aluminium paint on petrol tanks: reflects → cooler, less vapor; solar heaters black behind glass
- Earth gets a tiny share of the Sun's radiation and radiates to cold space → ≈ 15 °C, not 5800 K

Thermos flask: vacuum stops conduction and convection; silvered walls: poor emitter inside, reflector; cork or plastic stopper; insulating supports

Good cooking pot: high-k bottom (copper on stainless steel, $k \approx 16$ vs 400); low heat capacity; dull dark bottom, polished sides; poor-conductor handles; doesn't react with food

Sun's temperature

- Sun radiates $4\pi R^2 \sigma T^4$; all of it crosses a sphere of radius r: $4\pi r^2 S$
- equal → $T^4 = \frac{S}{\sigma}\left(\frac{r}{R}\right)^2$; $S = 1361$ W/m^2, $r = 1.496 \times 10^{11}$ m, $R = 6.96 \times 10^8$ m → ≈ 5770 K (effective temperature)

COMMON MISTAKES

✗ temperatures in °C in Stefan's law
✓ **kelvin**; conduction uses only a difference (K or °C same).

✗ double °C → 16 × radiation
✓ double the **absolute** temperature.

✗ in layers, different heat through each
✓ **same heat per second** through every layer.

✗ readings while the bar is warming
✓ only at the **steady state**.

✗ k depends on area and length
✓ only on the **material**.