IB DP PHYSICS · THEME B THE PARTICULATE NATURE OF MATTER · B.4 (HL ONLY) · ~8 MIN READ

B.4 Thermodynamics

The first law Q = ΔU + W, work done by a gas, isobaric, isovolumetric, isothermal and adiabatic processes on P–V diagrams, cycles and heat engines, entropy, the second law and the Carnot limit.

First law · W = PΔV · P–V diagrams · Adiabatic processes · Cycles & heat engines · Carnot efficiency · Entropy · Second law

RS by Riyaz Sir
mentorriyaz.in

No tag = **SL and HL** · HL ONLY HL students only · DATA BOOKLET given in the exam

M1 A1 how marks are awarded · highlight = comes up again and again · Test yourself at the end

IN 30 SECONDS

- **B.4 is HL only.** The **first law**, Q = ΔU + W, is conservation of energy for a gas: energy supplied by heating either raises the internal energy or does work as the gas expands.
- On a **P–V diagram** the area under a process is the work done; around a cycle the enclosed area is the net work.
- The **second law**: the entropy of an isolated system never decreases. So no heat engine can turn all of Q_h into work; the best possible efficiency is the **Carnot** value $1 - T_c/T_h$.

BY THE END YOU CAN

- Apply the first law with the correct signs. HL
- Calculate work from W = PΔV and from areas on P–V diagrams. HL
- Describe isovolumetric, isobaric, isothermal and adiabatic processes and use $PV^{5/3}$ = constant. HL
- Analyse cyclic processes and heat engine efficiency, including the Carnot limit. HL
- Calculate entropy changes with ΔS = ΔQ/T and $S = k_B \ln \Omega$, and state the second law. HL

1 The first law HL

$$Q = \Delta U + W$$ DATA BOOKLET

Q = energy supplied TO the gas by heating; W = work done BY the gas

- **Signs:** Q > 0 heating the gas, Q < 0 the gas loses energy. W > 0 the gas expands and does work, W < 0 work is done on the gas (compression). ΔU > 0 temperature rises.

$$W = P\Delta V$$ DATA BOOKLET

work done by a gas at constant pressure

$$\Delta U = \frac{3}{2}Nk_B\Delta T = \frac{3}{2}nR\Delta T$$ DATA BOOKLET

ideal monatomic gas: U depends only on T

WORKED EXAMPLE

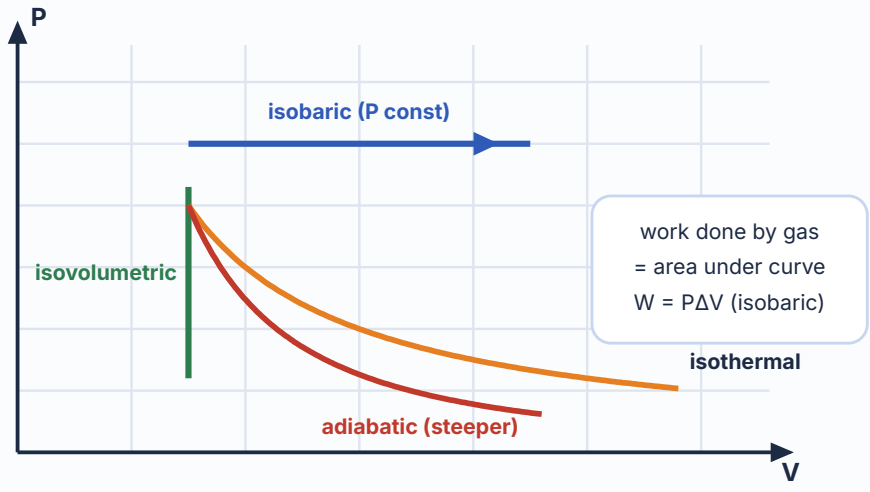
2.0 mol of a monatomic ideal gas expands at a constant 1.0×10^5 Pa from 0.040 m^3 to 0.060 m^3. Find W, ΔU and Q.

1. $W = P\Delta V = 1.0 \times 10^5 \times 0.020 =$ **2000 J** A1
2. $\Delta U = \frac{3}{2}nR\Delta T = \frac{3}{2}P\Delta V$ (since PV = nRT) = **3000 J** M1 A1
3. **Q = ΔU + W = 5000 J** A1

COMMON MISTAKE

Using the chemistry sign convention (work done ON the gas). In IB Physics, W in Q = ΔU + W is the work done BY the gas.

2 Processes on a P–V diagram HL



Four processes from the same starting point. The adiabatic curve is steeper than the isothermal one.

Process	Constant	First law becomes
isovolumetric (isochoric)	V	W = 0, so Q = ΔU
isobaric	P	Q = ΔU + PΔV
isothermal	T	ΔU = 0, so Q = W
adiabatic	no heat flow (Q = 0)	ΔU = −W

$$PV^{5/3} = \text{constant}$$ DATA BOOKLET

adiabatic process in an ideal monatomic gas

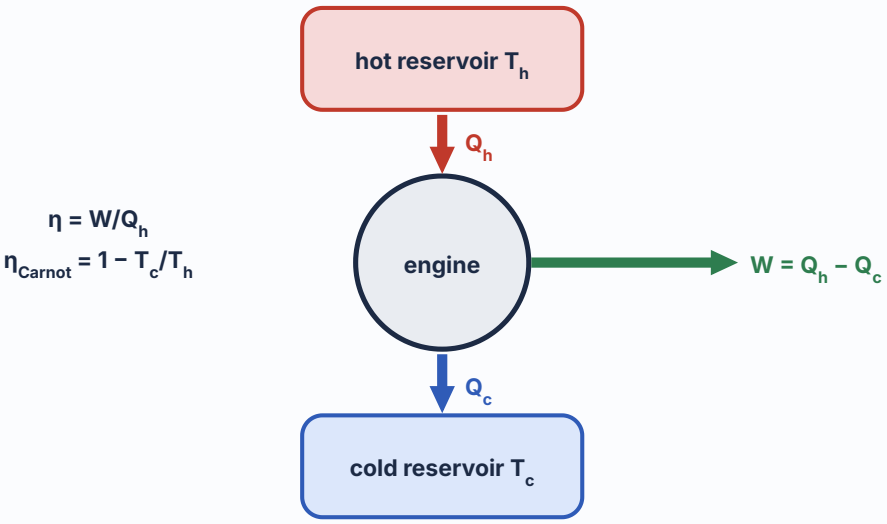
- **Adiabatic in practice:** very fast changes (no time for heat to flow) or well-insulated gases. Compressing a gas adiabatically heats it (a bicycle pump warms up); adiabatic expansion cools it (clouds form in rising air).

WORKED EXAMPLE

A monatomic gas at 1.0×10^5 Pa and 300 K is compressed adiabatically to half its volume. Find the new pressure and temperature.

1. $P_2 = P_1(V_1/V_2)^{5/3} = 1.0 \times 10^5 \times 2^{5/3} =$ **3.2×10^5 Pa** M1 A1
2. $T_2/T_1 = (P_2V_2)/(P_1V_1) = 3.17 \times 0.5 = 1.59$ M1
3. **$T_2 = 476$ K** A1

3 Cycles and heat engines HL



A heat engine takes in Q_h, does work W and must reject Q_c to a cold reservoir.

$$\eta = \frac{\text{useful work}}{\text{input energy}} = \frac{W}{Q_h}$$ DATA BOOKLET

efficiency of a heat engine

$$\eta_{Carnot} = 1 - \frac{T_c}{T_h}$$ DATA BOOKLET

the maximum possible efficiency between two reservoirs (temperatures in kelvin)

- **Cycle on a P–V diagram:** the gas returns to its starting state, so ΔU = 0 over the cycle and the net work equals the net heat in. Clockwise cycle = engine (net work done by the gas); the enclosed area is the net work.

WORKED EXAMPLE

A gas is taken round a rectangular cycle between 1.0×10^5 and 3.0×10^5 Pa and between 0.010 and 0.030 m^3. It absorbs 1.6×10^4 J per cycle. Find the net work and the efficiency.

1. area = $(3.0 - 1.0) \times 10^5 \times (0.030 - 0.010)$ = **4000 J** M1 A1
2. **η = 4000/16 000 = 25 %** A1

WORKED EXAMPLE

An engine works between 600 K and 300 K. Find its Carnot efficiency. Can it reach 60 %?

1. $\eta_C = 1 - 300/600$ = **50 %** A1
2. **no: 60 % would break the second law; real engines get less than 50 % because of friction and irreversible heat flow** R1

COMMON MISTAKE

Using Celsius in $1 - T_c/T_h$. Between 327 °C and 27 °C the answer is 50 %, not 1 − 27/327 = 92 %.

4 Entropy and the second law HL

$$\Delta S = \frac{\Delta Q}{T}$$ DATA BOOKLET

entropy change when energy ΔQ is transferred at temperature T (J K^{-1})

$$S = k_B \ln \Omega$$ DATA BOOKLET

Ω = number of microstates (arrangements) of the system

Entropy — a measure of the disorder of a system: the number of microscopic ways its particles can be arranged with the same total energy.

Second law — the entropy of an isolated system never decreases. Real (irreversible) processes in isolated systems increase entropy.

- **Clausius form:** heat never flows spontaneously from a cold body to a hot one. **Kelvin form:** no engine working in a cycle can convert all the heat it absorbs into work.
- **Local decreases are allowed** in systems that are not isolated (a fridge cools its contents, living things build order), as long as the surroundings gain at least as much entropy.

WORKED EXAMPLE

Find the entropy change when 1.0 kg of ice melts at 0 °C ($L_f = 3.34 \times 10^5$ J kg^{-1}).

1. ΔQ = 3.34×10^5 J at T = 273 K M1
2. **ΔS = $3.34 \times 10^5/273 = +1.2 \times 10^3$ J K^{-1}** A1

WORKED EXAMPLE

500 J flows from a body at 500 K to one at 250 K. Show that total entropy increases.

1. hot body: ΔS = −500/500 = −1.0 J K^{-1} M1
2. cold body: ΔS = +500/250 = +2.0 J K^{-1} M1
3. **total = +1.0 J K^{-1} > 0 ✓** R1

EXAM TIP

When asked why a heat engine needs a cold reservoir, answer with entropy: the engine's entropy returns to its starting value each cycle, so it must pass some entropy (Q_c/T_c) to the cold reservoir.

LINKING QUESTION

The Carnot limit decides how much electricity a power station can make from the heat of burning fuel or of fission (E.4), which is why cooling towers waste so much energy.

IDEA FOR YOUR IA / EXPLORATION

Use a Stirling engine or thermoelectric module between hot and cold water. Measure the output power at different temperature differences and compare the trend with the Carnot efficiency.

Test yourself — cover the answers first

QUICK CHECK

1. Write the first law and say what W means.
2. In which process is ΔU = 0?
3. What is Q in an adiabatic process?
4. How do you find the net work in a cycle on a P–V diagram?
5. Can entropy ever decrease?
6. What happens to S when Ω doubles?

EXAM-STYLE

7. 0.50 mol of monatomic gas is heated at constant volume from 300 K to 450 K. Find Q, W and ΔU.
8. A refrigerator removes 300 J from food at 270 K and releases 400 J to a kitchen at 300 K. Find the total entropy change.

Show answers

1. Q = ΔU + W; W is work done BY the gas
2. isothermal
3. zero
4. the area enclosed by the loop
5. Locally, in a non-isolated system, yes; for an isolated system, never.
6. it increases by $k_B \ln 2 = 9.6 \times 10^{-24}$ J K^{-1}
7. W = 0 (no volume change)
   ΔU = 1.5 × 0.50 × 8.31 × 150 = 935 J
   Q = ΔU = **935 J**
8. food: −300/270 = −1.11 J K^{-1}
   kitchen: +400/300 = +1.33 J K^{-1}
   total = **+0.22 J K^{-1}**, so the second law is obeyed

Stuck on a question?

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