inkPhysics

ANSWER BOOK

The first law of thermodynamics

Engineering physics · Year 13

AQA 3.11.2.1, 3.11.2.2, 3.11.2.3 · CIE 16.1.2, 16.2.1, 16.2.2 · OCR A 5.1.2(f), 5.1.4(i)

17 questions · 51 marks

NAVY EDITION

SECTION A · Warm-up

A1 $Q = \Delta U + W$ (1). Q is the heat supplied **to** the gas, ΔU the increase in its internal energy, and W the work done **by** the gas on its surroundings (1). Getting these two directions the right way round is what the sign of every later answer depends on. [2]

A2 It is the total kinetic energy of the random motion of its molecules (1). An ideal gas has no intermolecular potential energy, so its internal energy depends only on its absolute temperature (1). [2]

A3 Constant volume: $W = 0$, because the gas does not move its surroundings, so no work is done (1). Isothermal: $\Delta U = 0$, because the temperature is unchanged and the internal energy of an ideal gas depends only on temperature, so $Q = W$ (1). [2]

A4 A change in which no heat enters or leaves the gas, $Q = 0$, achieved by good insulation or by acting too quickly for heat to flow (1). Examples: the compression stroke of a diesel engine, or the barrel of a bicycle pump warming as you pump (1). [2]

A5 For a small increase in volume δV the gas does work $p\,\delta V$, the area of a thin strip under the curve (1). Adding all such strips between the initial and final volumes gives the total work, which is the area under the curve (1). Only at constant pressure does this reduce to the single rectangle $p\Delta V$. [2]

A6 W is negative (1), because W means the work done by the gas and here the surroundings do work on it instead. [1]

SECTION B · Standard

B1 $\Delta U = Q - W$ (1) $= 850 - 320 = +530$ J (1). The internal energy has risen, and for an ideal gas that means the temperature rises (1), though by less than 850 J of heating alone would give, because 320 J left as work. [3]

B2 W = area under the curve $= 34 \times 25 = 850$ J (1). $\Delta U = Q - W$ (1) $= 1200 - 850 = +350$ J (1). Counting squares is an accepted method here; $p\Delta V$ would only serve if the pressure were constant. [3]

B3 Adiabatic means no heat flow, so $Q = 0$ (1). Work is done on the gas, so in this convention $W = -500$ J, and $\Delta U = Q - W = 0 - (-500) = +500$ J (1). The internal energy rises, so the temperature rises (1). Writing W as +500 J flips the sign and predicts cooling, which is the standard error in every adiabatic compression question. [3]

B4 Isothermal, so pV = constant (1): $p_2 = 2.4 \times 10^5 \times 3.0/8.0 = 9.0 \times 10^4$ Pa (1). $\Delta U = 0$ for an isothermal change, so $Q = W$; the gas expands so W is positive, so heat flows into the gas at the same rate as it does work (1). Reaching for pV^γ = constant here is the standard error: that line belongs to the adiabat. [3]

B5 $p_1V_1^\gamma = p_2V_2^\gamma$, so $p_2 = p_1(V_1/V_2)^\gamma$ (1). $V_1/V_2 = 5.0$, and $5.0^{1.4} = 9.52$ (1), so $p_2 = 1.0 \times 10^5 \times 9.52 = 9.5 \times 10^5$ Pa (1). Note the pressure rises by more than the volume ratio of 5, because the gas heats as it is squeezed. [3]

B6 Rigid means constant volume, so $W = 0$ in both stages (1). Stage 1: $\Delta U = Q = +1200$ J (1). Stage 2: Q is negative because heat leaves, so $\Delta U = -400$ J. Overall $\Delta U = +800$ J (1), so the gas ends hotter than it began. [3]

B7 $\Delta V = 6.5 \times 10^{-3} - 1.5 \times 10^{-3} = 5.0 \times 10^{-3}$ m^3 (1). $W = p\Delta V = 8.0 \times 10^4 \times 5.0 \times 10^{-3} = 400$ J (1). $\Delta U = Q - W = 620 - 400 = +220$ J (1). Using the final volume instead of the change is the standard slip and gives a work more than five times too large. [3]

SECTION C · Stretch

C1 A to B: constant volume, so $W = 0$ J (1). B to C: $W = p\Delta V = 3.0 \times 10^5 \times 2.0 \times 10^{-3} = +600$ J (1). C to D: constant volume, so $W = 0$ J (1). D to A: the gas is compressed, so $W = 1.0 \times 10^5 \times (-2.0 \times 10^{-3}) = -200$ J (1). Net work per cycle $= 600 - 200 = +400$ J, which is exactly the area enclosed by the rectangle, $\Delta p \times \Delta V = 2.0 \times 10^5 \times 2.0 \times 10^{-3}$ (1). The gas returns to state A, so its temperature and hence ΔU return to their starting values and $\Delta U = 0$ over the cycle; the first law then gives net Q = net $W = +400$ J (1). Adding the four works without making the compression negative is the standard error, and it wrongly gives 800 J. [6]

C2 Compression ratio $V_1/V_2 = 18$ (1). $p_2 = p_1(V_1/V_2)^\gamma = 1.0 \times 10^5 \times 18^{1.4} = 1.0 \times 10^5 \times 57.2 = 5.72 \times 10^6$ Pa (1). Then pV/T is constant, so $T_2/T_1 = p_2V_2/p_1V_1 = 57.2/18 = 3.18$ (1), giving $T_2 = 300 \times 3.18 = 953$ K (1). No heat was supplied at all: the piston did work on the molecules, raising their mean kinetic energy and so the temperature, and about 950 K is above the ignition temperature of the fuel, so it ignites on injection (1). Working the temperature ratio in celsius, or assuming pV = constant, are the two standard errors. [5]

C3 The isothermal expansion does more work (1). On the p-V diagram the adiabat falls more steeply than the isotherm, so less area lies beneath it between the same two volumes, and work is that area (1). Physically, the isothermal gas is fed heat continuously, and with $\Delta U = 0$ every joule of that heat leaves as work (1). The adiabatic gas receives no heat at all, so with $Q = 0$ it must pay for its work out of its own internal energy, $\Delta U = -W$, and it cools as it expands, which lowers its pressure further and limits the work available (1). [4]

C4 Constant volume: $W = 0$, so $\Delta U = Q = +500$ J (1). Isothermal: $\Delta U = 0$, and $Q = W = +380$ J (1). Adiabatic: $Q = 0$ and $W = -260$ J because the work is done on the gas, so $\Delta U = -W = +260$ J (1). Overall $\Delta U = 500 + 0 + 260 = +760$ J. Check: total $Q = 500 + 380 + 0 = 880$ J and total $W = 0 + 380 - 260 = 120$ J, and $880 = 760 + 120$, so the ledger closes (1). The one sign that decides the whole question is the negative W of the final compression. [4]