3.12 Physics: Thermal Physics and Gases

AQA 7408 · Calculator allowed · about 125 minutes · Write-in edition

Total Marks

Name: _____ Date: ____ / ____ / _____

Answer ALL questions. Show all your working.

1 This question is about internal energy and the first law of thermodynamics.

(a) State what is meant by the internal energy of a system. **(2)**

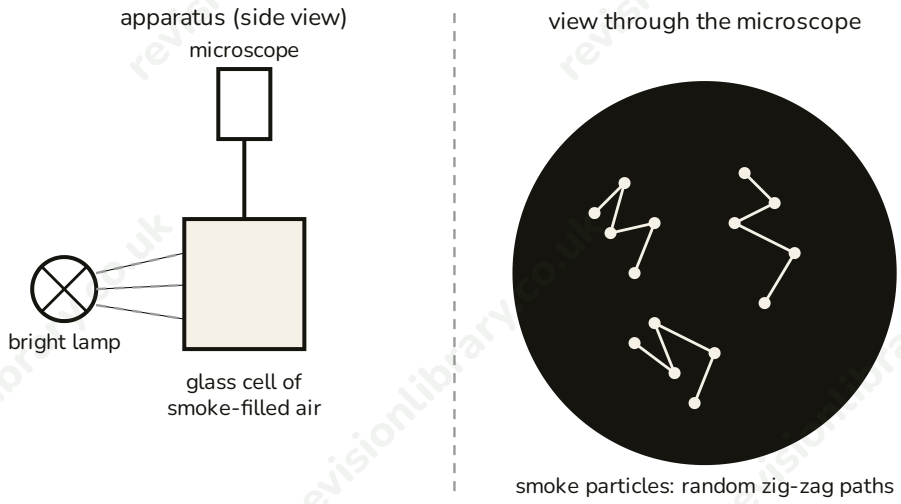
(b) A temperature of 15°C is to be used in a calculation involving the equation pV = nRT. Convert 15°C to kelvin. **(1)**

(c) Define the term specific latent heat of vaporisation of a substance. **(2)**

(d) A fixed mass of gas in a sealed cylinder is heated. The gas absorbs 450 J of thermal energy and, as it expands slightly against a piston, does 120 J of work on the surroundings. Using DeltaU = Q + W, where W is the work done on the gas, calculate the increase in internal energy of the gas. **(3)**

(Total for Question 1 is 8 marks)

2 In a smoke-cell experiment, smoke particles suspended in air are observed under a microscope, illuminated from the side. Small bright specks (the smoke particles) are seen to move continuously in random, zig-zag paths.



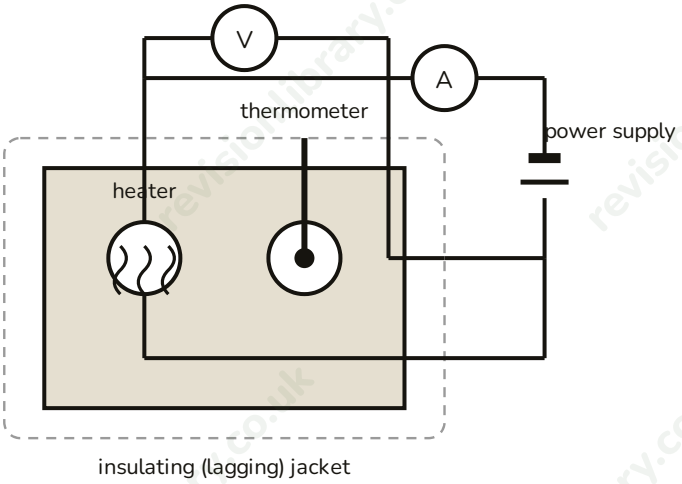
(a) Explain how these observations provide evidence for the kinetic theory model of a gas, in which air is made up of molecules in continuous, fast, random motion. **(4)**

(b) State the name given to this random, continuous motion of small particles suspended in a fluid, and give one other example (other than smoke in air) of where it can be observed. **(2)**

(Total for Question 2 is 6 marks)

3 This question is about an electrical specific-heat experiment to determine the specific heat capacity of a solid. A student is given a solid metal block, an electrical heater that fits into a hole drilled in the block, a thermometer that fits into a second hole, an ammeter, a voltmeter, a power supply, a stopclock, a top-pan balance and some lagging (insulating) material.

Explain how the student could use this apparatus to determine the specific heat capacity of the metal. In your answer you should include: the measurements the student would take and how they would be taken; how the measurements would be used to calculate a value for the specific heat capacity of the metal; one way of improving the accuracy of the final value obtained.



(Total for Question 3 is 6 marks)

4 A student carries out the electrical specific-heat experiment described in Question 3 to determine the specific heat capacity of an aluminium block of mass 1.000 kg. The heater is connected to a 12.0 V supply and draws a constant current of 4.0 A. The heater is switched on for 300 s, during which the block's temperature rises from 20.0°C to 36.0°C.

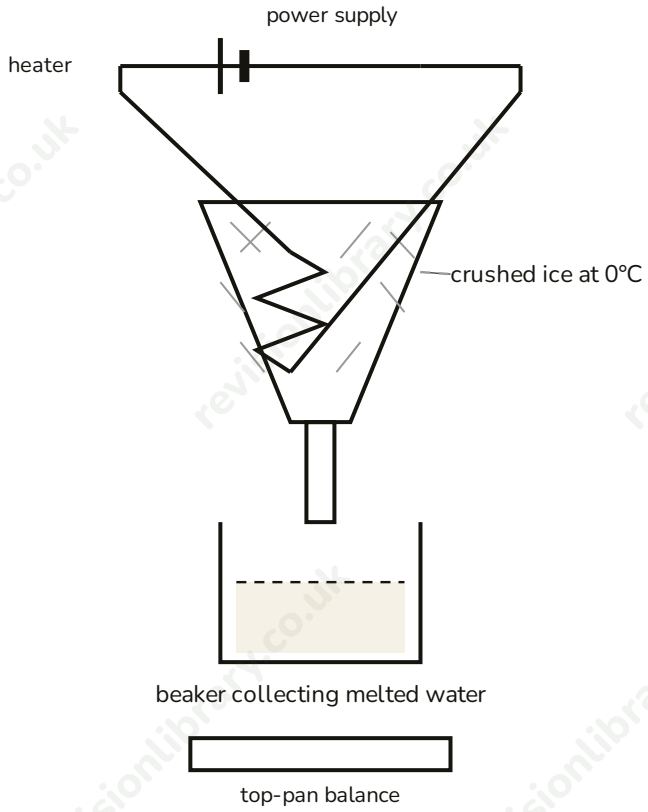
(a) Calculate the electrical energy supplied to the block during the 300 s heating time. **(2)**

(b) Show that the specific heat capacity of the aluminium block is approximately 900 J/(kg K). **(3)**

(c) The accepted value for the specific heat capacity of aluminium is 897 J/(kg K). Suggest one reason, in terms of energy transfer, why an experimental value obtained by this method would typically be higher than the accepted value, and explain how it leads to an overestimate. **(3)**

(Total for Question 4 is 8 marks)

5 In an experiment to determine the specific latent heat of fusion of ice, a 60 W electrical heater is placed in a funnel of crushed melting ice at 0°C, and the melted water (plus any water from background melting) is collected and weighed. With the heater switched on, 58.0 g of ice melts in 5.0 minutes. In a control run, with the heater switched off (but everything else unchanged), 4.0 g of ice melts in the same time due to heat gained from the surroundings.



(a) Explain, in terms of the kinetic theory model, why the temperature of the ice-water mixture remains at 0°C throughout the melting process, even though thermal energy is continuously being supplied. **(2)**

(b) Explain why a control run is carried out with the heater switched off, and how the result of this control run is used in the calculation. **(2)**

(c) Using the data given, calculate a value for the specific latent heat of fusion of ice. **(4)**

(Total for Question 5 is 8 marks)

6 A sample of neon gas (molar mass 20.2 g/mol) is enclosed in a rigid container of volume 5.00 x 10^{-3} m^3 at a pressure of 2.48 x 10^5 Pa and a temperature of 300 K. The gas may be treated as ideal. Take R = 8.31 J/(mol K) and N_A = 6.02 x 10^{23} /mol. The equation $pV = (1/3)Nm(\bar{c^2})$, where the bar denotes a mean, relates the pressure and volume of the gas to the number of molecules N, the mass m of one molecule, and the mean square speed ($\bar{c^2}$) of the molecules.

(a) Show that the number of neon molecules in the container is about 3 x 10^{23}. **(3)**

(b) Calculate the mass, in kg, of one neon atom. **(2)**

(c) Using $pV = (1/3)Nm(\bar{c^2})$, calculate the mean square speed ($\bar{c^2}$) of the neon atoms, and hence calculate their root mean square speed. **(5)**

(Total for Question 6 is 10 marks)

7 The mean translational kinetic energy of a molecule of an ideal gas is given by (3/2)kT, where k is the Boltzmann constant ($k = 1.38 \times 10^{-23}$ J/K) and T is the thermodynamic temperature.

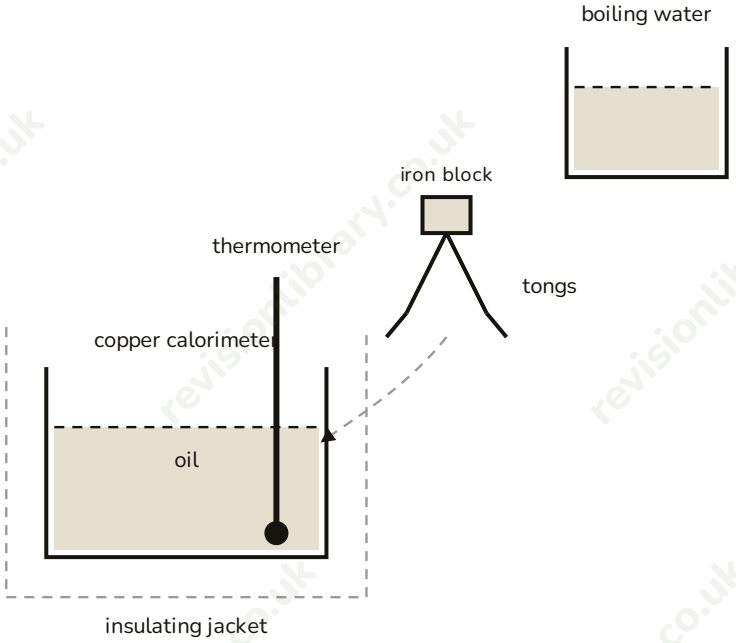
(a) Calculate the mean translational kinetic energy of a gas molecule at a temperature of 25°C. **(3)**

(b) Calculate the temperature, in degrees Celsius, at which the mean translational kinetic energy of a gas molecule would be double the value calculated in part (a). **(3)**

(c) Hence explain why doubling the Celsius temperature of a gas (for example, from 25°C to 50°C) does not double the mean kinetic energy of its molecules. **(2)**

(Total for Question 7 is 8 marks)

8 A student uses the method of mixtures to find the specific heat capacity of an oil. A copper calorimeter of mass 0.150 kg (specific heat capacity of copper = 385 J/(kg K)) contains 0.200 kg of the oil, both initially at 18.0°C. A 0.080 kg block of iron (specific heat capacity of iron = 450 J/(kg K)), heated to 96.0°C in boiling water, is quickly transferred into the oil. The mixture reaches a final steady temperature of 28.0°C. Assume no heat is lost to the surroundings.



(a) Calculate the thermal energy released by the iron block as it cools from 96.0°C to 28.0°C. **(2)**

(b) Calculate the thermal energy gained by the copper calorimeter as its temperature rises from 18.0°C to 28.0°C. **(2)**

(c) Assuming no heat losses, use your answers to parts (a) and (b) to calculate the specific heat capacity of the oil. **(4)**

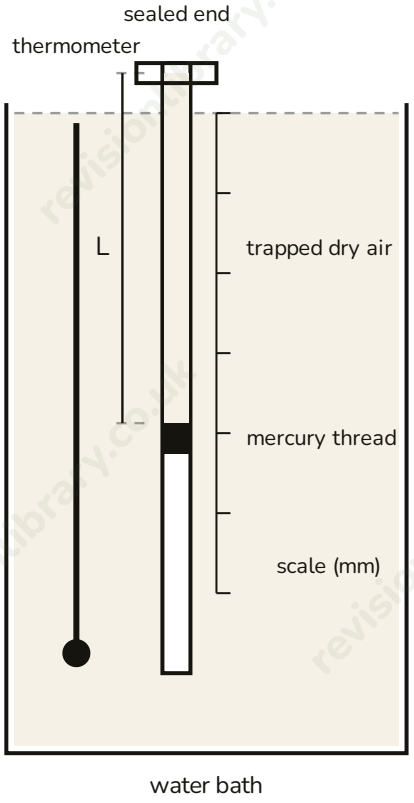
(d) State and explain one modification to the method that would reduce the systematic error caused by heat loss to the surroundings. **(2)**

(Total for Question 8 is 10 marks)

9 This question is based on the required practical: investigation of Charles's law. A fixed mass of dry air is trapped by a short thread of mercury in a capillary tube, sealed at one end, held vertically with the sealed end up. The tube is placed in a water bath, and the length L of the trapped air column is measured (using a scale alongside the tube) at each of several temperatures θ. The results are:

θ / °C : 20.0, 40.0, 60.0, 80.0, 100.0
L / mm : 117.2, 125.2, 133.2, 141.2, 149.2

A graph of L against θ is found to be a straight line.



(a) Explain why the length L of the trapped air column can be used as a measure of the volume of the trapped gas. **(1)**

(b) Explain why it is important that the pressure of the trapped gas remains constant throughout this experiment. **(2)**

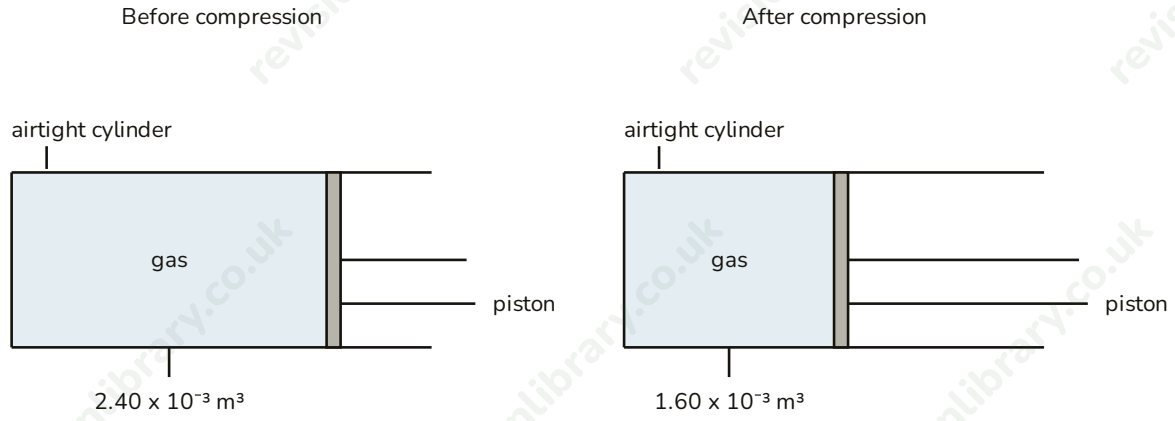
(c) Calculate the gradient of the graph of L against θ. **(3)**

(d) By extrapolating the graph (or using the equation of the line), determine the value of absolute zero, in degrees Celsius, suggested by these results. **(3)**

(Total for Question 9 is 9 marks)

10 A fixed mass of an ideal gas is held in a cylinder fitted with a frictionless, airtight piston. Take the molar gas constant R = 8.31 J/(mol K) and the Avogadro constant $N_A = 6.02 \times 10^{23}$ /mol.

Diagram NOT accurately drawn



(a) State two of the basic assumptions of the kinetic theory model of a gas that lead to the ideal gas laws. **(2)**

(b) Explain what is meant by the term ideal gas. **(2)**

(c) Initially the gas has a volume of 2.40×10^{-3} m^3 at a pressure of 1.5×10^5 Pa and a temperature of 300 K. The piston is pushed in, at constant temperature, until the volume becomes 1.60×10^{-3} m^3. Calculate the new pressure of the gas. **(3)**

(d) The gas is then heated at constant volume (1.60×10^{-3} m^3) from 300 K until its pressure becomes 3.00×10^5 Pa. Calculate the final temperature of the gas. **(3)**

(e) Use the initial conditions ($p = 1.5 \times 10^5$ Pa, $V = 2.40 \times 10^{-3}$ m^3, T = 300 K) with the ideal gas equation $pV = nRT$ to calculate the amount, in moles, of gas in the cylinder. **(3)**

(f) Given that the molar mass of the gas is 32 g/mol, calculate the mass of gas in the cylinder, in grams. **(2)**

(Total for Question 10 is 15 marks)

Mark scheme · 3.12 Physics: Thermal Physics and Gases

Question 1

(a) the sum of the randomly distributed kinetic energies of the particles (atoms/molecules) of the system, due to their motion (oe) **B1**

(a) plus the sum of the (randomly distributed) potential energies of the particles, arising from the forces/bonds between them (oe) **B1**

(a) Answer: Internal energy is the sum of the randomly distributed kinetic energies (due to their motion) and potential energies (due to the forces/bonds between them) of all the particles in a system.

(b) 288 K, cao **A1**

(b) Answer: 288 K

(c) the (thermal) energy required to change the state of a unit mass (1 kg) of a substance from liquid to vapour/gas (oe) **B1**

(c) without any change in temperature (at constant temperature, at the boiling point) (oe) **B1**

(c) Answer: The energy required to change the state of 1 kg of a substance from liquid to vapour, without any change in temperature.

(d) identifies that, because the gas does 120 J of work on the surroundings, the work done ON the gas is W = -120 J **M1**

(d) correct substitution: DeltaU = Q + W = 450 + (-120) **M1**

(d) DeltaU = 330 J (increase), cao **A1**

(d) Answer: DeltaU = +330 J (an increase in internal energy of 330 J)

Question 2

(a) the smoke particles are much larger (and heavier) than individual air molecules, so they are visible as bright specks by reflected/scattered light, whereas the air molecules themselves are far too small to see **B1**

(a) each smoke particle is continuously bombarded (collided with) on all sides by the (invisible) fast-moving air molecules **B1**

(a) at any instant, the number and direction of these collisions is not perfectly balanced (random/unequal from different directions), so the smoke particle experiences a net, randomly-changing (unbalanced) force **B1**

(a) this net random force causes the particle's random, zig-zag motion; since this can only be caused by collisions with individually moving particles, it is indirect evidence that air is made of discrete, fast-moving, randomly-moving molecules, supporting the kinetic theory model (oe) **B1**

(a) Answer: The visible smoke particles are bombarded from all sides by the much smaller, invisible, fast-moving air molecules. Because the number and direction of these collisions is randomly unequal at any instant, the smoke particle receives a net, constantly-changing force, producing its random zig-zag motion. Since this motion can only be caused by collisions with individual moving particles, it is indirect evidence that air is made up of molecules in continuous random motion, as the kinetic theory model proposes.

(b) Brownian motion **B1**

(b) any valid other example, e.g. pollen grains (or dust particles) suspended in water and viewed under a microscope also show random, continuous movement **B1**

(b) Answer: Brownian motion; for example, pollen grains (or dust particles) suspended in water and viewed under a microscope also show this random continuous movement.

Question 3

Level 1 Basic, largely isolated statements about the apparatus or measurements, with little reference to how they would be used to calculate specific heat capacity, and no clear improvement suggested. **1-2**

Level 2 Most of the required measurements are described (mass, current and/or potential difference, time, temperature rise), and there is some attempt to link these to a calculation of specific heat capacity, but the method or the equation used is incomplete, unclear, or contains errors. An improvement may be stated but not linked to improved accuracy. **3-4**

Level 3 A complete, logically ordered method is given: measuring the mass of the block; inserting the heater and thermometer (using oil for good thermal contact); insulating the block; recording the initial temperature; supplying a measured current and potential difference for a measured time; recording the temperature rise; correctly calculating the electrical energy supplied and using E = mcDeltaTheta to find c. A valid, clearly explained improvement to accuracy is also given. **5-6**

Indicative content:

- Measure the mass m of the metal block using a top-pan balance.
- Insert the electrical heater into one hole and the thermometer into the other, using a small amount of oil in each hole to improve thermal contact.
- Wrap/lag the block in insulating material (e.g. expanded polystyrene or felt) to reduce (unwanted) heat loss to the surroundings.
- Record the initial temperature theta1 of the block.
- Connect the heater to a power supply, with an ammeter in series (to measure current I) and a voltmeter connected across the heater (to measure potential difference V).
- Switch on the heater and start a stopclock at the same instant; record the time t for which the heater is switched on.
- Switch off the heater, and continue to monitor the temperature until it stops rising; record the maximum (final) temperature theta2, so the temperature rise is DeltaTheta = theta2 - theta1.
- Calculate the electrical energy supplied to the block: E = VIt (or E = I^2Rt).
- Rearrange E = mcDeltaTheta to calculate the specific heat capacity: c = E/(mDeltaTheta).
- Improvement: correct for heat lost to the surroundings during heating, e.g. by plotting a cooling correction graph and extrapolating back to the moment heating stopped, by improving the insulation/lagging, or by using a joulemeter to measure electrical energy directly rather than relying on separately-read V, I and t.

Question 4

(a) correct substitution into E = VIt **M1**

(a) E = 14400 J (14.4 kJ), cao **A1**

(a) Answer: E = 14400 J

(b) identifies the temperature rise DeltaTheta = 36.0 - 20.0 = 16.0 K **M1**

(b) rearranges E = mcDeltaTheta to c = E/(mDeltaTheta) and substitutes their E from (a), m = 1.000 kg and DeltaTheta = 16.0 K **M1**

(b) c = 900 J/(kg K), with clear supporting working shown (as required for a show-that question) **A1**

(b) Answer: c = 900 J/(kg K)

(c) not all of the electrical energy calculated (E = VIt) actually ends up raising the temperature of the block; some is lost to the surroundings (by conduction, convection and/or radiation) despite the lagging (oe) **B1**

(c) this means the true energy that caused the measured temperature rise is less than the calculated E, but the student's calculation uses the full E as if all of it went into the block **B1**

(c) since c = E/(mDeltaTheta) and the measured DeltaTheta is unaffected while E is (in effect) too large relative to it, the calculated value of c comes out higher than the true value (oe) **B1**

(c) Answer: Some of the electrical energy supplied is lost to the surroundings rather than heating the block, despite the lagging. Because the calculation assumes all of the electrical energy raised the block's temperature, using the full E in c = E/(mDeltaTheta) makes the calculated specific heat capacity higher than the true value.

Question 5

(a) while melting, the energy supplied increases the potential energy of the particles (by weakening/breaking the bonds holding them in the fixed structure of the solid), not their kinetic energy (oe) **B1**

(a) since temperature depends on the mean kinetic energy of the particles, and this is unchanged during melting, the temperature stays constant at 0°C until all the ice has melted (oe) **B1**

(a) Answer: The energy supplied during melting increases the potential energy of the particles (breaking the bonds of the solid structure) rather than their kinetic energy. Since temperature depends on mean kinetic energy, the temperature stays at 0°C until all the ice has melted.

(b) some ice melts anyway due to (background) heat gained from the surroundings (the room, the funnel, etc.), even without the heater; this is a systematic error/confounding effect that would otherwise be wrongly attributed to the heater **B1**

(b) the mass melted in the control run is subtracted from the mass melted with the heater on, to find the mass melted due to the heater alone **B1**

(b) Answer: Ice melts due to heat gained from the surroundings even without the heater, which would otherwise be wrongly credited to the heater. The mass melted in the control run is subtracted from the mass melted with the heater on, isolating the mass melted by the heater's energy alone.

(c) mass melted due to the heater alone = 58.0 - 4.0 = 54.0 g = 0.0540 kg **M1**

(c) electrical energy supplied E = Pt = 60 x 300 = 18000 J **M1**

(c) correct substitution into L = E/m **M1**

(c) L = 3.3 x 10^5 J/kg (accept 3.2-3.4 x 10^5 J/kg), awrt 2 sf **A1**

(c) Answer: L = 3.3 x 10^5 J/kg

Question 6

(a) rearranges pV = nRT to n = pV/(RT) and substitutes correctly, finding n = 0.497 mol **M1**

(a) multiplies by the Avogadro constant: N = n x N_A **M1**

(a) N = 2.99 x 10^{23} (approximately 3 x 10^{23}), with clear supporting working shown **A1**

(a) Answer: N is approximately 3 x 10^{23} molecules

(b) converts molar mass to kg/mol and divides by the Avogadro constant: m = M/N_A **M1**

(b) m = 3.36 x 10^{-26} kg, awrt 3 sf **A1**

(b) Answer: m = 3.36 x 10^{-26} kg

(c) rearranges to make (c^2) the subject: (c^2) = 3pV/(Nm), recognising that N x m equals the total mass of the gas sample **M1**

(c) correct substitution using their N (part a), m (part b), or the equivalent total gas mass **M1**

(c) (c^2) = 3.70 x 10^5 m^2/s^2 (accept 3.6-3.8 x 10^5 m^2/s^2), ft **A1**

(c) takes the square root of their (c^2) to find the root mean square speed **M1**

(c) c_{rms} = 608 m/s (accept 600-615 m/s), awrt 3 sf, ft **A1**

(c) Answer: (c^2) = 3.70 x 10^5 m^2/s^2; c_{rms} = 608 m/s

Question 7

(a) converts temperature to kelvin: T = 25 + 273 = 298 K **M1**

(a) correct substitution into (3/2)kT **M1**

(a) 6.17 x 10^{-21} J, awrt 3 sf **A1**

(a) Answer: 6.17 x 10^{-21} J

(b) recognises that kinetic energy is directly proportional to thermodynamic temperature, so doubling the kinetic energy requires doubling the temperature in kelvin, ft from (a) **M1**

(b) T_{new} = 2 x 298 = 596 K **M1**

(b) 323°C, awrt 3 sf, ft from candidate's T in (a) **A1**

(b) Answer: 323°C

(c) mean kinetic energy is proportional to the thermodynamic (kelvin) temperature, not the Celsius temperature (oe) **M1**

(c) doubling the Celsius value (e.g. 25°C to 50°C) is only a change from 298 K to 323 K, which is nowhere near double the kelvin temperature, so the kinetic energy is far from doubling (oe) **A1**

(c) Answer: Kinetic energy depends on the thermodynamic (kelvin) temperature, not the Celsius value. Doubling 25°C to 50°C only changes T from 298 K to 323 K, a small fractional increase, so the kinetic energy does not come close to doubling.

Question 8

(a) correct substitution into E = mcDeltaTheta, with DeltaTheta = 96.0 - 28.0 = 68.0 K **M1**

(a) E = 2448 J, cao **A1**

(a) Answer: E = 2448 J

(b) correct substitution into E = mcDeltaTheta, with DeltaTheta = 28.0 - 18.0 = 10.0 K **M1**

(b) E = 577.5 J (accept 578 J), cao **A1**

(b) Answer: E = 577.5 J

(c) applies energy conservation: energy gained by oil = energy released by iron - energy gained by calorimeter, ft from (a) and (b) **M1**

(c) correctly finds the temperature rise of the oil, DeltaTheta = 10.0 K **M1**

(c) rearranges c = E/(mDeltaTheta) and substitutes correctly **M1**

(c) c(oil) = 935 J/(kg K), awrt 3 sf, ft **A1**

(c) Answer: c(oil) = 935 J/(kg K)

(d) a valid modification, e.g. use a lid on the calorimeter, add extra insulating lagging around the calorimeter, or transfer the iron block as quickly as possible **B1**

(d) explains this reduces heat loss to the surroundings during the experiment, so the energy assumed to be gained by the oil (and hence the calculated specific heat capacity) is closer to the true value (rather than an overestimate) **B1**

(d) Answer: For example, fit a lid to the calorimeter (or add more lagging around it). This reduces heat loss to the surroundings during the experiment, so the calculated specific heat capacity of the oil is closer to its true value, rather than being overestimated.

Question 9

(a) the capillary tube has a constant (uniform) cross-sectional area A, so the volume of the trapped gas V = A x L is directly proportional to its length L **B1**

(a) Answer: The tube has a uniform cross-sectional area, so volume V = A x L is directly proportional to length L.

(b) Charles's law (V/T = constant) is only valid at constant pressure; with the trapped air above the mercury thread, its pressure is atmospheric pressure minus the (roughly constant) pressure head of the mercury thread: pGas = pAtm - ρ g h, where ρ is the mercury density and h is the vertical height of the thread **B1**

(b) if the pressure changed during the experiment, any change in L could be caused (at least partly) by the pressure change rather than only by the temperature change, so the relationship being tested (V proportional to T) would not be validly investigated **B1**

(b) Answer: Charles's law only holds at constant pressure. If the pressure of the trapped gas changed during the experiment, changes in L could be due to the pressure change rather than solely the temperature change, invalidating the test of V proportional to T.

(c) selects two data points (e.g. first and last) and identifies rise (change in L) and run (change in θ) **M1**

(c) correct substitution, e.g. (149.2 - 117.2)/(100.0 - 20.0) **M1**

(c) gradient = 0.400 mm/°C, cao (allow any consistent correct pair of points) **A1**

(c) Answer: gradient = 0.400 mm/°C

(d) finds the intercept L0 of the line at θ = 0, using L = L0 + (gradient x θ) and a data point, e.g. L0 = 117.2 - (0.400 x 20.0) **M1**

(d) sets L = 0 (the theoretical volume at absolute zero) and rearranges to find θ = -L0/gradient **M1**

(d) θ = -273°C (accept -270 to -277°C), consistent with the accepted value of absolute zero **A1**

(d) Answer: θ = -273°C

Question 10

(a) the volume occupied by the gas molecules themselves is negligible compared with the volume occupied by the gas (oe) **B1**

(a) there are no (negligible) intermolecular forces between molecules except during collisions, and collisions between molecules (and with the container walls) are perfectly elastic (oe). Any two creditable assumptions. **B1**

(a) Answer: For example: the volume of the gas molecules is negligible compared with the volume of the container; there are no intermolecular forces except during (perfectly elastic) collisions.

(b) a gas that obeys the ideal gas equation pV = nRT exactly, at all pressures, volumes and temperatures (oe) **B1**

(b) equivalently, a theoretical gas whose molecules have negligible volume and no intermolecular forces except during (elastic) collisions, i.e. one that perfectly matches the kinetic theory model (oe) **B1**

(b) Answer: An ideal gas is one that obeys pV = nRT exactly under all conditions; its molecules are treated as having negligible volume and no intermolecular forces except during perfectly elastic collisions.

(c) applies Boyle's law: p1V1 = p2V2 **M1**

(c) correct substitution: p2 = (1.5 x 10^5 x 2.40 x 10^{-3})/(1.60 x 10^{-3}) **M1**

(c) p2 = 2.25 x 10^5 Pa, cao **A1**

(c) Answer: p2 = 2.25 x 10^5 Pa

(d) applies the pressure law at constant volume: p2/T2 = p3/T3 **M1**

(d) correct substitution, using p2 = 2.25 x 10^5 Pa (ft from (c)): T3 = 300 x (3.00 x 10^5/2.25 x 10^5) **M1**

(d) T3 = 400 K, cao (allow ft from candidate's (c)) **A1**

(d) Answer: T3 = 400 K

(e) rearranges pV = nRT to n = pV/(RT) **M1**

(e) correct substitution: n = (1.5 x 10^5 x 2.40 x 10^{-3})/(8.31 x 300) **M1**

(e) n = 0.144 mol, awrt 3 sf **A1**

(e) Answer: n = 0.144 mol

(f) mass = n x molar mass, using candidate's n from (e), ft **M1**

(f) mass = 4.62 g, awrt 3 sf **A1**

(f) Answer: mass = 4.62 g