1 (a) (i) One of the assumptions of the kinetic theory of gases is that molecules make *elastic collisions.* State what is meant by an elastic collision.

(ii) State **two** more assumptions that are made in the kinetic theory of gases.

(3)

(b) One mole of hydrogen at a temperature of 420 K is mixed with one mole of oxygen at 320 K. After a short period of time the mixture is in *thermal equilibrium*.

(i) Explain what happens as the two gases approach and then reach thermal equilibrium.

(ii) Calculate the average kinetic energy of the hydrogen molecules before they are mixed with the oxygen molecules.

(4)

(Total 7 marks)

2 (a) (i) Write down the equation of state for *n* moles of an ideal gas.

(ii) The molecular kinetic theory leads to the derivation of the equation

$$pV = \frac{1}{3} Nm\overline{c^2},$$

where the symbols have their usual meaning.

State **three** assumptions that are made in this derivation.

(4)

(b) Calculate the average kinetic energy of a gas molecule of an ideal gas at a temperature of 20 °C.

(3)

(c) Two different gases at the same temperature have molecules with different mean square speeds.
Explain why this is possible.

(2)

(Total 9 marks)

3 (a) The air in a room of volume 27.0 m^3 is at a temperature of 22 °C and a pressure of 105 kPa.

Calculate

(i) the temperature, in K, of the air,

(ii) the number of moles of air in the room,

(iii) the number of gas molecules in the room.

(5)

(b) The temperature of an ideal gas in a sealed container falls. State, with a reason, what happens to the

(i) mean square speed of the gas molecules,

(ii) pressure of the gas.

(4)

(Total 9 marks)

4 (a) State **two** quantities which increase when the temperature of a given mass of gas is increased at constant volume.

(i)

(ii)

(2)

(b) A car tyre of volume 1.0×10^{-2} m^3 contains air at a pressure of 300 kPa and a temperature of 290K. The mass of one mole of air is 2.9×10^{-2} kg. Assuming that the air behaves as an ideal gas, calculate

(i) n, the amount, in mol, of air,

(ii) the mass of the air,

(iii) the density of the air.

(5)

(c) Air contains oxygen and nitrogen molecules. State, with a reason, whether the following are the same for oxygen and nitrogen molecules in air at a given temperature.

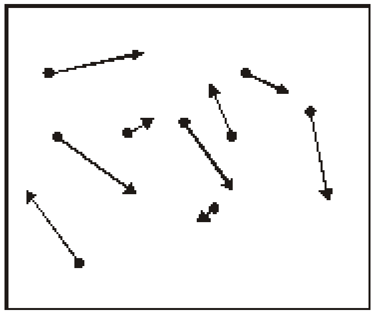
(i) The average kinetic energy per molecule

(ii) The r.m.s. speed

(4)

(Total 11 marks)

5 The diagram below shows a number of smoke particles suspended in air. The arrows indicate the directions in which the particles are moving at a particular time.



(a) (i) Explain why the smoke particles are observed to move.

___

___

(1)

(ii) Smoke particles are observed to move in a random way. State **two** conclusions about air molecules and their motion resulting from this observation.

___

___

___

___

(2)

(b) A sample of air has a density of 1.24 kg m^{-3} at a pressure of 1.01×10^5 Pa and a temperature of 300 K.

the Boltzmann constant = 1.38×10^{-23} J K^{-1}

(i) Calculate the mean kinetic energy of an air molecule under these conditions.

(2)

(ii) Calculate the mean square speed for the air molecules.

(3)

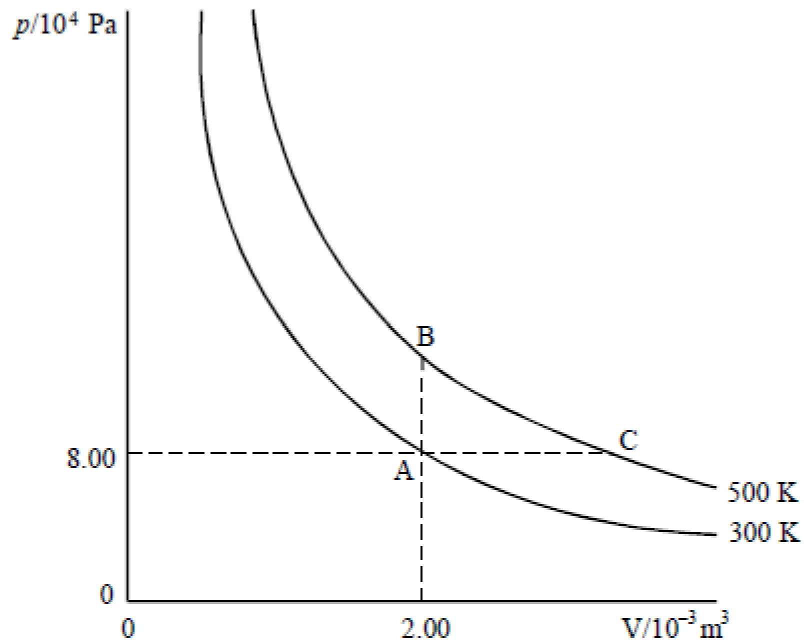
(iii) Explain why, when the temperature of the air is increased to 320 K, some of the molecules will have speeds much less than that suggested by the value you calculated in part (b)(ii).

(2)

(Total 10 marks)

6 (a) The diagram shows curves (not to scale) relating pressure p, and volume, V, for a fixed mass of an ideal monatomic gas at 300K and 500K. The gas is in a container which is closed by a piston which can move with negligible friction.

molar gas constant, R, = 8.31 J mol^{-1} K^{-1}



(i) Show that the number of moles of gas in the container is 6.4×10^{-2}.

(ii) Calculate the volume of the gas at point C on the graph.

(3)

(b) (i) Give an expression for the total kinetic energy of the molecules in one mole of an ideal gas at kelvin temperature T.

____

(ii) Calculate the total kinetic energy of the molecules of the gas in the container at point A on the graph.

Explain why this equals the total internal energy for an ideal gas.

____

____

____

____

(4)

(c) Defining the terms used, explain how the first law of thermodynamics, $\Delta Q = \Delta U + \Delta W$, applies to the changes on the graph

(i) at constant volume from A to B,

____

____

____

(ii) at constant pressure from A to C.

____

____

____

(5)

(d) Calculate the heat energy absorbed by the gas in the change

(i) from A to B,

____

____

____

(ii) from A to C

(3)

(Total 15 marks)

7 (a) Use the kinetic theory of gases to explain why

(i) the pressure exerted by an ideal gas increases when it is heated at constant volume.

(ii) the volume occupied by an ideal gas increases when it is heated at constant pressure.

(4)

(b) A quantity of 0.25 mol of air enters a diesel engine at a pressure of 1.05×10^5 Pa and a temperature of 27°C. Assume the gas to be ideal.

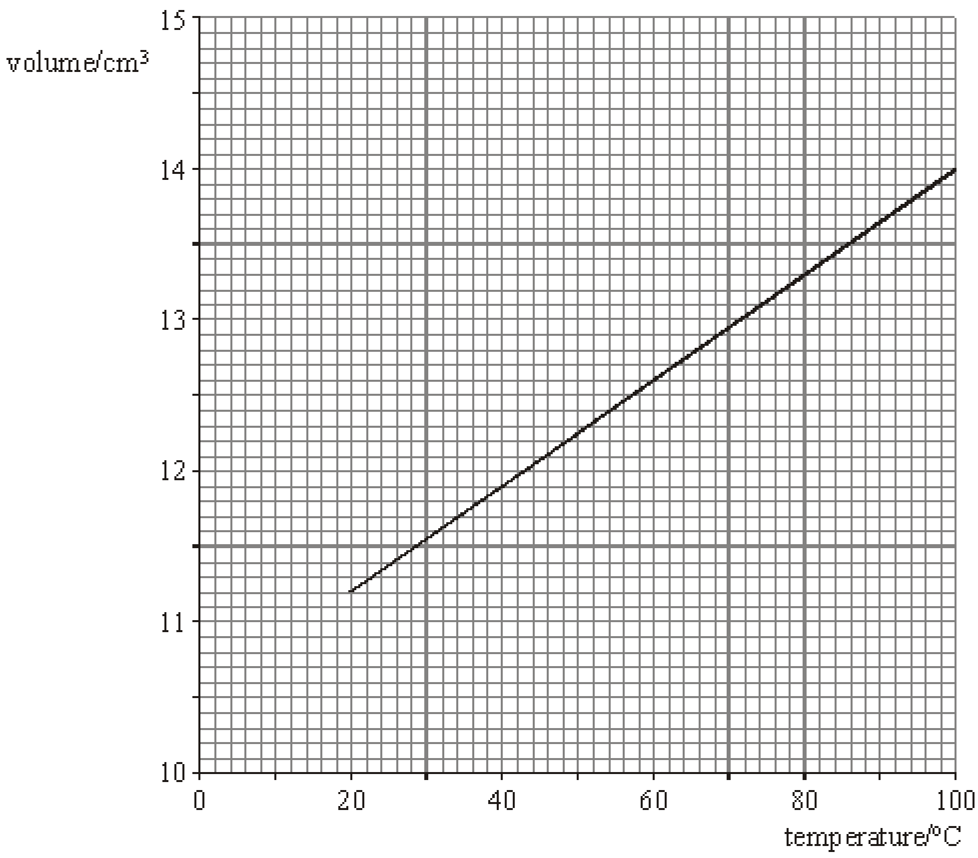
(i) Calculate the volume occupied by the gas.

(ii) When the gas is compressed to one twentieth of its original volume the pressure rises to 7.0×10^6 Pa. Calculate the temperature of the gas immediately after the compression.

(4)

(Total 8 marks)

8 The graph in the figure below shows the best fit line for the results of an experiment in which the volume of a fixed mass of gas was measured over a temperature range from 20°C to 100°C. The pressure of the gas remained constant throughout the experiment.



(a) Use the graph in the figure to calculate a value for the absolute zero of temperature in °C. Show clearly your method of working.

(4)

(b) Use data from the graph in the figure to calculate the mass of gas used in the experiment. You may assume that the gas behaved like an ideal gas throughout the experiment.

gas pressure throughout the experiment	=	1.0×10^5 Pa
molar gas constant	=	8.3 J mol^{-1} K^{-1}
molar mass of the gas used	=	0.044 kg mol^{-1}

(5)

(Total 9 marks)

9 Helium is a monatomic gas for which all the internal energy of the molecules may be considered to be translational kinetic energy.

molar mass of helium = 4.0×10^{-3} kg
the Boltzmann constant = 1.38×10^{-23} J K^{-1}
the Avogadro constant = 6.02×10^{23} mol^{-1}

(a) Calculate the kinetic energy of a tennis ball of mass 60 g travelling at 50 m s^{-1}.

___

___

___

(1)

(b) Calculate the internal energy of 1.0 g of helium gas at a temperature of 48K.

___

___

___

___

___

___

(3)

(c) At what temperature would the internal energy of 1.0 g of helium gas be equal to the kinetic energy of the ball in part (a).

___

___

(1)
(Total 5 marks)

10 A 1.0 kΩ resistor is thermally insulated and a potential difference of 6.0 V is applied to it for 2.0 minutes. The thermal capacity of the resistor is 9.0 J K^{-1}. The rise in temperature, in K, is

A 1.3×10^{-3}

B 8.0×10^{-3}

C 0.48

D 0.80

(Total 1 mark)

11 At a certain temperature, the root-mean-square speed of the molecules of a fixed volume of an ideal gas is c. The temperature of the gas is changed so that the pressure is halved. The root-mean-square speed of the molecules becomes

A $\frac{c}{4}$

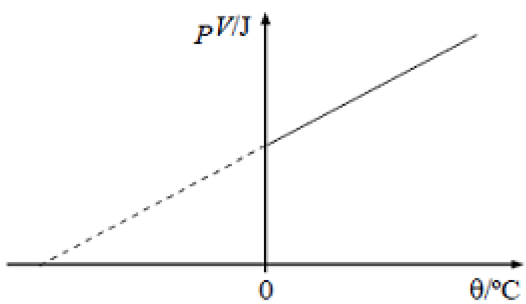
B $\frac{c}{2}$

C $\frac{c}{\sqrt{2}}$

D 2c

(Total 1 mark)

12 The graph shows the relation between the product *pressure* × *volume*, pV, and temperature, θ, in degrees celsius for 1 mol of an ideal gas for which the molar gas constant is R.



Which one of the following expressions gives the gradient of this graph?

A $\frac{1}{273}$

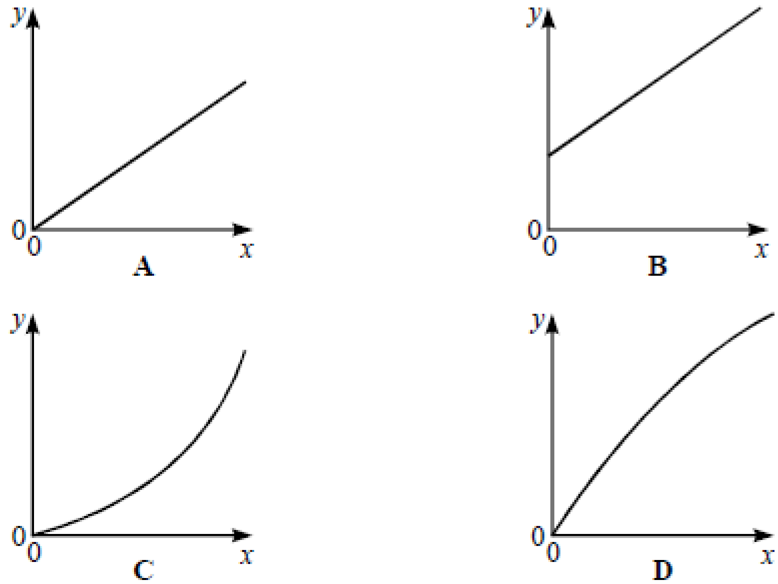
B $\frac{pV}{\theta}$

C $\frac{pV}{(\theta - 273)}$

D R

(Total 1 mark)

13 Which one of the graphs below shows the relationship between the internal energy of an ideal gas (y-axis) and the absolute temperature of the gas (x-axis)?



(Total 1 mark)

14 A fixed mass of gas occupies a volume V. The temperature of the gas increases so that the root mean square velocity of the gas molecules is doubled.
What will the new volume be if the pressure remains constant?

A $\frac{V}{2}$ ☐

B $\frac{V}{\sqrt{2}}$ ☐

C $2V$ ☐

D $4V$ ☐

(Total 1 mark)

15 The temperature of a hot liquid in a container falls at a rate of 2 K per minute just before it begins to solidify. The temperature then remains steady for 20 minutes by which time all the liquid has all solidified.

What is the quantity $\frac{\text{Specific heat capacity of the liquid}}{\text{Specific latent heat of fusion}}$?

A $\frac{1}{40}\,\mathrm{K}^{-1}$ ☐

B $\frac{1}{10}\,\mathrm{K}^{-1}$ ☐

C $10\ \mathrm{K}^{-1}$ ☐

D $40\ \mathrm{K}^{-1}$ ☐

(Total 1 mark)

Mark schemes

1 (a) (i) a collision in which kinetic energy is conserved **(1)**

(ii) molecules of a gas are identical
[or all molecules have the same mass] **(1)**
molecules exert no forces on each other except during impact **(1)**
motion of molecules is random
[or molecules move in random directions] **(1)**

volume of molecules is negligible (compared to volume of container)
[or very small compared to volume of container or point particles] **(1)**
time of collision is negligible (compared to time between collisions) **(1)**
Newton‘s laws apply **(1)**
large number of particles **(1)** (any two)

3

(b) (i) the hot gas cools and cooler gas heats up
until they are at same temperature
hydrogen molecules transfer energy to oxygen molecules
until **average k.e.** is the same
(any two **(1)** **(1)**)

(ii) (use of $E_k = \frac{3}{2}kT$ gives) $E_k = \frac{3}{2} \times 1.38 \times 10^{-23} \times 420$ **(1)**

$= 8.7 \times 10^{-21}$ J (8.69×10^{-21} J)

4

[7]

2 (a) (i) $pV = nRT$ **(1)**

(ii) all particles identical or have same mass **(1)**
collisions of gas molecules are elastic **(1)**
inter molecular forces are negligible (except during collisions) **(1)**
volume of molecules is negligible (compared to volume of container) **(1)**
time of collisions is negligible **(1)**
motion of molecules is random **(1)**
large number of molecules present
(therefore statistical analysis applies) **(1)**
monamatic gas **(1)**
Newtonian mechanics applies **(1)**

max 4

(b) $E_k = \frac{3RT}{2N_A}$ or $\frac{3}{2}kT$ **(1)**

$= \frac{3 \times 8.31 \times 293}{2 \times 6.02 \times 10^{23}}$ **(1)**

$= 6.1 \times 10^{-21}$ J **(1)** (6.07×10^{-21} J)

3

(c) masses are different **(1)**
hence because E_k is the same,
mean square speeds must be different **(1)**

2

[9]

3 (a) (i) T (=273 + 22) = 295 (K) **(1)**

(ii) $pV = nRT$ **(1)**
$105 \times 10^3 \times 27 = n \times 8.31 \times 295$ **(1)**
$n = 1160$ (moles) **(1)** (1156 moles)
(allow C.E. for T (in K) from (i)

(iii) $N = 1156 \times 6.02 \times 10^{23} = 7.0 \times 10^{26}$ **(1)** (6.96×10^{26})

5

(b) (i) decreases **(1)**

because temperature depends on mean square speed (or $\overline{c^2}$)
[or depends on mean E_k] **(1)**

(ii) decreases **(1)**
as number of collisions (per second) falls **(1)**
rate of change of momentum decreases **(1)**

[or if using $pV = nRT$
decreases **(1)**
as V constant **(1)**
as n constant **(1)**]

[or if using p = $1/3\rho\overline{c^2}$
decrease **(1)**
as ρ is constant **(1)**

as $\overline{c^2}$ is constant **(1)**]

max 4

[9]

4 (a) (i) pressure **(1)**

(ii) (average) kinetic energy
[or rms speed] **(1)**

(2)

(b) (i) $pV = nRT$ **(1)**

$$n = \frac{1.0 \times 10^{-2} \times 300 \times 10^{3}}{8.31 \times 290} \textbf{ (1)}$$

= 1.20 (mol) **(1)** (1.24 mol)

(ii) mass of air = 1.24 × 29 × 10^{-3} = 0.036 kg **(1)**
(allow e.c.f from(i))

(iii) $\rho = \frac{0.0360}{1 \times 10^{-2}} = 3.6 \text{ kg m}^{-3}$ (allow e.c.f. from (ii))

(5)

(c) (i) same **(1)**
because the temperature is the same **(1)**

The Quality of Written Communication marks were awarded primarily for the quality of answers to this part.

(ii) different **(1)**
because the mass of the molecules are different **(1)**

(4)

[11]

5 (a) (i) collisions with/bombardment by air molecules
(condone particles)

B1

1

(ii) motion of air molecules (“they are“) random
(in all directions)

B1

fast moving

B1

max 2

air molecules small or much smaller than smoke particles

B1

(b) (i) 3/2kT or substituted values (independent of powers)

do not allow all equations written

C1

6.21×10^{-21} J

A1

2

(ii) pV = 1/3 Nm<c^2>

C1

relates Nm/V to ρ

C1

2.4×10^5 m^{2}s^{-2}

A1

(allow compensation of ½ m<c^2> for 1)

3

(iii) there will be a range of speeds

B1

there will be molecules with lower speeds
than mean /average
means higher and lower values

B1

2

[10]

6 (a) (i) correct p and V from graph **(1)**

$$n = \frac{8.0 \times 10^4 \times 2.00 \times 10^{-3}}{8.31 \times 300}$$ **(1)** (= 0.0064 mol)

(ii) $V_2 = V_1 \frac{T_2}{T_1}$ = 3.3×10^{-3} m^3 **(1)**

(3)

(b) (i) $\frac{3}{2} RT$ or $\frac{3}{2} N_A kT$ **(1)**

(ii) total kinetic energy $\left(=\frac{3}{2}nRT\right)$ = 1.5 × 8.3 × 0.064 × 300 **(1)** = 239 J **(1)**

molecules have no potential energy **(1)**
no attractive forces [or elastic collisions occur] **(1)**

(max 4)

(c) ΔQ = heat entering (or leaving) gas

ΔU = change (or increase) in internal energy

ΔW = work done

[**(1) (1)** for three definitions, deduct one for each incorrect or missing]

(i) $\Delta Q = \Delta U$ **(1)**
temperature rises but no work done **(1)**

(ii) $\Delta Q = \Delta U + \Delta W$ **(1)**
temperature rises and work done in expanding **(1)**

(max 5)

(d) (i) $\Delta U = \frac{3}{2}\, nR(500 - 300)$ = 159 J **(1)** (= ΔQ)

(ii) $p\Delta V = 8.0 \times 10^4 \times (3.3 - 2.0) \times 10^{-3}$ = 104 J **(1)**
$\therefore \Delta Q = \Delta U + p\Delta V$ = 263 J **(1)**

(3)

[15]

7 (a) (i) more collisions (with wall) per second **(1)**
and more momentum change per collision **(1)**
greater force because more momentum change per second (greater pressure) **(1)**

(ii) (same pressure) faster molecules so more momentum change per collision **(1)**
greater volume, fewer collisions per second [or greater volume
to maintain same pressure] **(1)**

max 4

(b) (i) $V = \left(\frac{nRT}{p}\right) = \frac{0.250 \times 8.31 \times 300}{1.05 \times 10^5}$ **(1)** = 5.94×10^{-3} m^3 **(1)**

(ii) $T_2 = \left(\frac{T_1 V_2 P_2}{p_1 V_1}\right) = \frac{300 \times 7.0 \times 10^6}{1.05 \times 10^5 \times 20}\left[or\ T_2 = \left(\frac{p_2 V_2}{nR}\right) = \frac{7.0 \times 10^6 \times 5.94 \times 10^{-3}}{8.31 \times 0.25 \times 20}\right]$ **(1)**
= 1000 K (727 °C) **(1)**

4

[8]

8 (a) m = gradient = 0.035 ± 0.001 (cm^2 $°C^{-1}$)

B1

c = intercept = 10.5 ± 0.1 (cm^2)

B1

absolute zero = -c/m

C1

= -300 ± 10 °C *some relevant working must be seen*

A1

4

or a meaningful attempt to use similar triangles

M1

an accurate value for the base found

C1

adjustment to the base (if appropriate)

C1

answer = -300 ± 10 °C

A1

4

or *relevant use of* $V_1/T_1 = V_2/ T_2$

M1

valid introduction of **unknown** temperature

A1

consistent solution of the equation

C1

answer = -300 ± 10 °C

C1

4

(b) statement of *or use of* pV = nRT

C1

accurate reading from the line

C1

Celsius converted to Kelvin *(+273 or + answer to part (a))*

C1

$n = 4.52 \times 10^{-4}$ **or** 4.11×10^{-4} *or* 4.2×10^{-4} *(ΔV/ΔT)* (mol)

A1

$m = n \times 0.044$ ($m = 4.52 \times 0.044 = 2.0 \times 10^{-5}$ kg)

B1

5

[9]

9

(a) kinetic energy of ball = $\frac{1}{2} \times mv^2 = \frac{1}{2} \times 0.060 \times (50)^2 = 75$ J **(1)**

(1)

(b) kinetic energy of one atom $\frac{3}{2}kT$ **(1)** ($\frac{3}{2} \times 1.38 \times 10^{-23} \times T$)

one gram contains $\frac{1}{4} \times N_A$ (= 1.5×10^{23}) atoms **(1)**

total internal energy = $1.5 \times 10^{23} \times \frac{3}{2} \times 1.38 \times 10^{-23} \times 48 = 150$ J **(1)**

(3)

(c) energy of helium gas at 48 K is twice that of tennis ball
∴energies equal when helium gas has a temperature of 24 K **(1)**

(1)

[5]

10 C

[1]

11 C

[1]

12 D

[1]

13 A

[1]

14 D

[1]

15 A

[1]

Examiner reports

1 Candidates answered this question confidently although there was still some confusion as to acceptable assumptions made in the kinetic theory. The term 'thermal equilibrium' did cause some confusion to weaker candidates but full marks for this question were quite common.

2 This question also gave good discrimination. In part (a) the better candidates made very few errors and scored high marks but the less able candidates found it more difficult and were unable to come up with three assumptions of the kinetic theory.

The calculation in part (b) caused problems and even candidates who selected the correct expression had difficulties. The commonest of these was failing to convert the temperature to Kelvin.

Part (c) was answered correctly by only the best candidates and although many did identify that molecular mass was important, they could not quite explain why.

3 Again candidates found this a demanding question and a significant minority were not even able to convert the temperature from Celsius to Kelvin in part (a). In the same section, the calculation of number of moles of gas and the number of gas molecules also proved difficult and significant figure errors were common.

Part (b) realised better answers, although many candidates did not seem to appreciate that temperature is related to the mean kinetic energy and not to the kinetic energy of an individual molecule.

4 In part (a) most candidates could only give one correct quantity. This was usually pressure. Very few gave the average kinetic energy. The calculation in part (b) was generally well done, with the most common error being the inability to convert kPa to Pa. This however only incurred a one-mark penalty.

Candidates found part (c) much more difficult and even those who knew the correct answer were often not able to express themselves clearly. It was apparent from many answers that candidates could remember the appropriate equations but were not as secure in their conceptual understanding.

5 (a) (i) Most candidates recognised that the random motion of the smoke particles was due to collision with air molecules. A minority simply mentioned Brownian movement without any explanation.

(ii) The majority of candidates suggested that air molecules moved randomly but few were able to link a second property, which could be inferred from the observation of the smoke particles.

(b) (i) Most candidates were able to quote the correct equation and substitute appropriate values to gain the answer 6.21×10^{-21} J. A minority of candidates used $\frac{2}{3}kT$ or missed the minus sign for the power of 10.

(ii) Although most candidates recognised the equation $pV = \frac{1}{3} Nm\langle c^2\rangle$, a high proportion failed to see how the density related to this equation and then either fudged its substitution, or else made no progress beyond quoting the equation. A significant number of candidates went on to quote the rms speed and were then penalised if they had not quoted the mean square value with its unit.

(iii) Few candidates gave a totally convincing argument that there was a distribution of molecular speeds and that at a higher temperature there would still be molecules moving with speeds well below the mean speed.

6 It was surprising to find that this was a popular question. The large majority of answers suggested that it had been a poor choice of question for many candidates. However, part (a) was almost universally answered correctly. For a significant number of candidates the three marks scored represented the total mark for the whole question. Very few correct answers were seen to part (b)(i). The words "one mole" were largely ignored and, for those candidates who did not ignore them, they were read as "one molecule" and the Avogadro constant appeared in the denominator of the equation.

Errors abounded in part (b)(ii) because candidates had not read the question sufficiently carefully. Very few candidates were able to go back to part (a) and identify correctly the temperature **and** the number of moles present. In consequence, the large majority of answers related either to one mole or one molecule. A good number of candidates knew exactly why the calculated value represented the total internal energy, i.e. because there are no intermolecular forces (or zero potential energy), but a larger number had absolutely no idea and either left the part blank or simply restated the question.

Parts (c) and (d) attracted the poorest answers in the entire section. Confusion abounded over the meanings of the terms in the First Law of Thermodynamics. The only term which could be defined with any certainty was that for external work done, ΔW. Most answers had many contradictions. In part (c)(ii) candidates could not come to terms with the fact that heat energy input had to be shared between changes in **both** internal energy and work done. Most candidates thought that, in part (c)(ii), the internal energy remained constant in spite of the fact that there was an obvious temperature change. There was widespread evidence that candidates had only a very superficial grasp of thermodynamics and acquired little skill in the interpretation of p−V graphs, which was at the heart of this question. Very few correct answers were seen to part (d) and it was very disappointing to see that there are candidates at Advanced level who still confuse heat and temperature. Thus, a significant number of candidates gave 200 J as the answer to part (d)(i). It was almost inevitable that those candidates who could not answer part (c) would also have difficulty with part (d), but some were able to give a partially correct answer in calculating the work done. For many candidates, this was their complete answer to part (d)(ii). Only a very small minority could calculate the changes in internal energy.

7 Part (a) proved to be difficult. In part (a)(i) the effect of the increase in the number of collisions per second with the container was often appreciated, although in too many answers 'more' was written instead of 'more frequent'. Mention of momentum was less common and a precise statement that the change in momentum per collision increased was rare. Increased force per collision was common but gained no credit.

This lack of understanding made part (a)(ii) even more difficult, as even those candidates who said that for constant pressure the volume had to increase to reduce the number of collisions per second could not say why, and many thought that the number of collisions had to remain constant. Many candidates tried to answer macroscopically, used the gas law in terms of $\overline{c^2}$ or referred to the first law of thermodynamics.

In contrast, most candidates scored full marks in part (b). Some candidates unwisely introduced other units than m^3 , e.g. dm^3 and cm^3 , with varying success. Only a small proportion of the candidates forgot to change the temperature to K. A surprising number of candidates misread one-twentieth, mostly as one-twelfth.

8 This was expected to be a challenging question so it is especially pleasing that so many candidates gained at least half of the marks and some of them all of the marks.

(a) The examiners anticipated several ways of successfully finding a value for absolute zero from the data presented in the graph. The candidates used all of these and some others as well. Candidates who attempted the *V/T = constant* route often got bogged down in their figures and at some stage anticipated the answer by adding 273 to the unknown temperature.

(b) This question was usually answered well with the most common errors being a failure to convert from Celsius to Kelvin and/or an incorrect conversion from cm^3 to m^3.